



# Geological Survey Paper 17:

## Structural Geology of northern Tasmania An Overview and Structural Synthesis

### Part 2: The Ulverstone Metamorphic Sheet and the West Ulverstone Imbricate Zone

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Isoclinally folded Proterozoic quartzite within a ~620 m long, elongated, shear zone-bounded quartzite pod at Picnic Point, Ulverstone. Seagull Islet (horizon mid photo) is part of the quartzite. The core of the pod is a major, inclined plunging, tight synformal fold (photo centre foreground) that is truncated and bounded by zones of mylonitic quartzite and high strain pelite. One of the shear zones trends from mid-photo left to the photo centre and is marked by the low area occupied by quartzite rubble. This Seagull Islet pod is the largest and best-exposed example of a macro-shear lozenge. It is part of a series of elongated, tapered pods in the low-grade Ulverstone-Oonah metamorphic sheet as carapace to the Forth Metamorphic sheet. The pods are enveloped by structurally intercalated schistose quartzite, quartz-mica schist, mica-quartz schist, deformed pebble conglomerate and phyllite. The phyllites contain rootless and attenuated isoclinally folded quartz veins.

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## ***Abstract***

*The Ulverstone Metamorphic Sheet is a strongly deformed, greenschist facies, allochthonous ~ 1.5 km thick slice of Neoproterozoic siliclastic protolith. It is derived from the subducted and exhumed edge of the former Tasmanian microcontinent and is part of a stacked series of metamorphic sheets. These include the overlying low-grade, sub-greenschist facies Oonah sheet, also of Neoproterozoic protolith, and the underlying high-grade Forth metamorphic sheet of Mesoproterozoic protolith. The sheets are separated by higher strain, shear zone subduction-exhumation interfaces. Some of the contacts are overprinted by younger, Devonian east-directed, thrust-reverse faults. Each sheet has distinct and different structural geometry and fabrics. There is a marked contrast in strain, metamorphic grade and style of deformation across the main contacts. The Ulverstone-Forth coastal platforms provide a unique window into the structural relationships within and between the External Zone low-grade (L-G) Neoproterozoic-Early Cambrian sequences and the Internal Zone high-grade (H-G) metamorphic rocks.*

*The West Ulverstone Imbricate Zone represents the faulted and imbricated contact between the L-G Oonah Sheet and the upper part of the Ulverstone Metamorphic Sheet. It is made up of two major fault slices separated by the Westbank and Ulverstone Fault Zones and includes the Singleton Fault Zone as a Devonian fault-reactivated contact between the Oonah L-G Sheet and the Ulverstone Sheet in the Goat Island Fault Slice (Fault Slice 1). The West Ulverstone Slice (Fault Slice 2) shows a "welded" foliation-parallel interface between the L-G Oonah Sheet and the Ulverstone Sheet, without significant Devonian fault reactivation. This strain transition should be typical/representative of contacts between sheets at the deeper levels of the obduction stack, whereas at shallower levels brittle faulting and mélangé occupy the contacts. Broken formation and mélangé zones occur at the base of the Oonah L\_G sheet and at the base of the Ulverstone L-G Sheet, preserved within the Devonian reactivated Westbank and Ulverstone Fault Zones*

*The uppermost part of the Ulverstone Metamorphic Sheet (Picnic Point wave-cut platform) features a homoclinal, west-dipping stack of intensely deformed, interfingering lithologies within transposition layering, where lithological boundaries are sub-parallel to the dominant foliation (Sm/S2). The lithologies include tapering lenses of strongly deformed pebble conglomerate, mica-quartz schist, quartz-mica schist, mylonitic platy quartzite and phyllite enveloping lozenges of quartzite at varying scales. This sequence grades into the margin of the quartzite Seagull Islet macro-shear lozenge that is characterized by shear zones of mylonitic platy quartzite interdigitating with quartz-mica phyllite. The structurally lowest part of the Ulverstone Metamorphic Sheet (East Ulverstone wave-cut platform) transitions from foliated zones to intensely foliated platy quartzite into mica-quartz schist towards the non-exposed interface with the Forth Metamorphic Sheet.*

*The Ulverstone Metamorphic Sheet is strongly to intensely deformed throughout, and shows significant strain characterised by intense transposition foliation, schistose to mylonitic zones and shear lozenge augen at all scales. Folds tend to be asymmetric S-vergent fold pairs many within shear lozenges. Shear zone propagation in and around these lozenges results in the segmentation and isolation of quartzite pods, indicating a form of shear zone cannibalisation of the larger quartzite bodies. The major structural elements of the Ulverstone Metamorphic Sheet, apart from the intense transposition layering, are large-scale macro-shear lozenges. The largest is the Seagull Islet macro-shear lozenge a ~620 m long x ~60 m wide, elongated, pod-like quartzite body with rounded, tapered terminations. The core of the Seagull Islet Shear Lozenge is an inclined plunging, isoclinal, synformal macro-fold within quartzite, bounded by high strain zones. The internal structures within the synformal pod reflect and record the structural transition of a thick, bedded quartzite unit into a lozenge enveloped by quartz mylonites and schist of high strain zones. Overprinting fold sets and refolding of the early isoclinal folds in the synform core suggest a complex history of shear and refolding with fold development during progressive general/simple shear.*

*The interference relationships between two distinct, "late" upright fold sets at Seagull Islet are characterized by their axial surface strike trends and fold plunges. The dominant 360°-010° trending folds exhibit greater lateral continuity and appear to isolate the 345°-355° trending folds, leading to complex fold interference patterns. The N-S fold set (F2b) is dominant, displaying greater amplitudes and continuous hinge lines, while the N-NW trending (F2a) folds are restricted in occurrence. The third-generation folds (F2b) have larger amplitudes, which allow them to override the earlier F2a folds, isolating their hinges.*

*The Oonah L-G Sheet is preserved within Fault Slices 1 and 2 that make up the West Ulverstone Imbricate Zone. The sub-greenschist facies sandstone/mudstone sequence, particularly within the West Ulverstone beach slice (Fault Slice 2) is internally folded by upright-horizontal folds. These folds have overall steeply west-dipping axial surfaces and associated S2 cleavage with moderate to gently plunging fold axes. Within the slice there is no apparent variation in strain. The Westbank Siding slice (Fault Slice 1) is largely homoclinal west-dipping although poly-deformed and folded within some fault-bounded panels as part of the Devonian fault stack in the hanging wall to the Singleton Fault.*

*The Ulverstone-Forth coastal section has had a complex faulting history with offsets and displacements that are necessary to explain the observed juxtaposition of sheets and the incorporation of Togari blocks in sheet-contact zone mélanges. These are:*

- *N-over-S emplacement of the Early Cambrian exhumation/obduction stack of the fault bounded Oonah, Ulverstone and Forth Metamorphic Sheets*
- *W-down Middle Cambrian normal faulting to create the northern part of the Dundas Graben.*
- *W-over-E Devonian thrusting with short-cut thrusts initiating off the steep west-dipping normal faults.*

*The North coast shows a different sheet stacking and transport sense to the Tyennan Domain with discordance across the Fossey Graben suggesting a major change in structural/tectonic evolution. This supports an inferred east-west trending transform fault in the Cambrian subduction margin, a fundamental break in the east-directed subduction of the Tasmanian microcontinent. The inferred transform fault was associated with a change in plate motion to the north of the transform involving north-over-south exhumation of subducted sheets. It also facilitated the middle Cambrian development of the E-W trending Fossey Graben.*

## Structural Geology of northern Tasmania— An Overview and Structural Synthesis

### PART 2: THE ULVERSTONE METAMORPHIC SHEET AND THE WEST ULVERSTONE IMBRICATE ZONE

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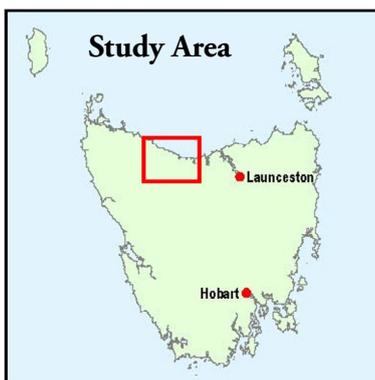
#### 1.0 INTRODUCTION

Northern Tasmania, particularly the almost continuous coastal exposures along the north coast, provides unique a window into the structural relationships between deeply subducted, high-grade (H-G) metamorphic rocks (Forth Metamorphic Complex/Sheet) and overlying, allochthonous, low-grade (L-G) Neoproterozoic-Early Cambrian sequences (Figure 1). The L-G sequences occur as a series of fault/shear zone-bounded sheets, including the greenschist facies Ulverstone Sheet (Neoproterozoic protolith), the sub-greenschist facies Oonah Sheet (Neoproterozoic protolith) and the obducted Early Cambrian oceanic (chert-basalt) Luina Sheet (Figures 1 and 2). The exposures provide the most accessible exposure of the contact between the External and Internal Zones of Berry (2014).

All of these sheets represent different parts of, and/or slices from different levels of a Cambrian margin subduction and exhumation system (see Berry, 2014; Mulder et al., 2018; Gray et al., 2023). Each sheet has distinct and different structural geometry and fabrics. There is a marked contrast in strain, metamorphic grade and style of deformation across the main contacts, as well as a reactivation of the earlier subduction-exhumation thrusts overprinted by younger, east-directed thrust-reverse faults.

This publication is the second in a series of MRT Geological Survey papers dealing with the structural character and inter-relationships of the major lithotectonic elements of northern Tasmania. These include:

- 1) H-G Forth Metamorphic Sheet (GSP16)
- 2) L-G Ulverstone Metamorphic Sheet (this paper)
- 3) L-G Burnie-Oonah Sheet
- 4) Penguin-Luina Sheet
- 5) Arthur Structural and Metamorphic Zone



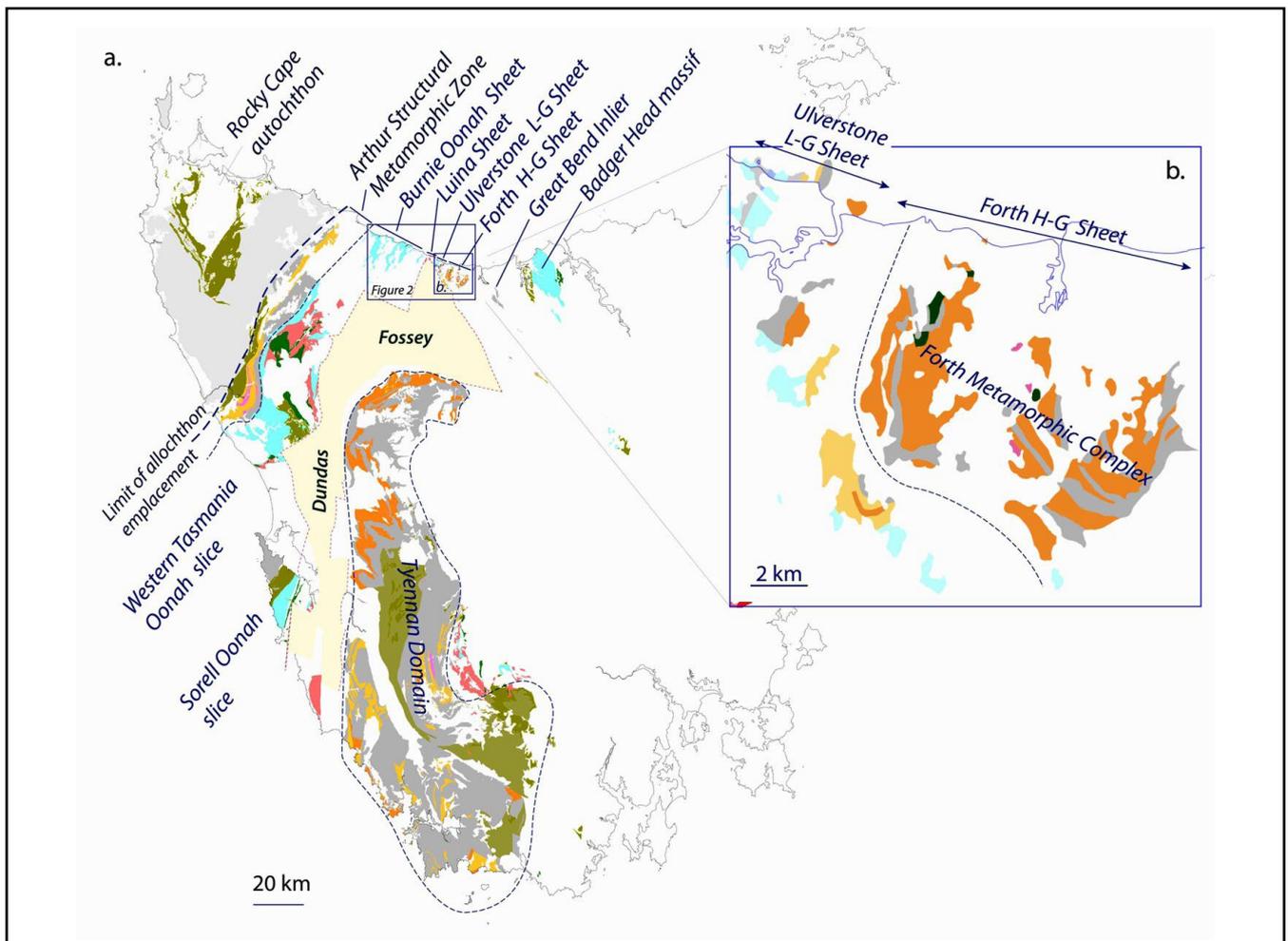


Figure 1. The major tectonic elements of western Tasmania shown in a). Map base is Mineral Resources Tasmania 1:25,000 and 1:250,000 digital geological atlas. b) Enlarged map with the location of the Ulverstone-Forth Metamorphic Complex. The approximate Ulverstone-Forth Metamorphic Complex map sheet polygon boundaries are 5448000 mS (northern boundary), 5430500 mS (southern boundary), 425000 mE (western boundary) and 444200 mE (eastern boundary).

## 2.0 BACKGROUND

The Ulverstone Metamorphic Sheet is a greenschist facies metamorphosed, highly strained, strongly deformed slice of quartzite, phyllite and quartz-pebble conglomerate (slice 2a, Figure 3). It is considered a deformed and metamorphosed Neoproterozoic Oonah-correlate (Mulder et al., 2018) that structurally sits above the H-G Forth Metamorphic Sheet (Figures 1, 2 and 3). It is best exposed along the west Ulverstone foreshore from Goat Island to Picnic Point to East Ulverstone beach (Figure 4). It represents the Ulverstone Metamorphics of Burns (1963a, 1964).

The western, uppermost part of the Ulverstone Sheet, west of Picnic Point, includes an imbricated and repeated contact between the overlying, relatively unmetamorphosed, sandstone-mudstone sequence of the Oonah Sheet (slice 2b, Figure 3) and the underlying, greenschist facies Ulverstone Metamorphic Sheet. This is the West Ulverstone Imbricate Zone and includes fault-breccia zones in scaly mudstone matrix mélangé with blocks of Togari Group and the Ulverstone Metamorphic Sheet. The main part of the sheet is exposed on the coast from Picnic Point to East Ulverstone beach and in the poorly outcropping inland part of the sheet (the orange area 2a, Figure 3).

## 2.1 Previous Mapping

An index map for mapping and structural data sources for the Ulverstone-Forth region is shown in Figure 5. Kerry Burns undertook mapping in the Dial Range in the early 1960s as part of a PhD at the University of Tasmania (Burns, 1963a) while on staff at the Department of Mines. The mapping led to publication of the Devonport 1:63,360 Quadrangle (Burns, 1963b) and the Devonport Explanatory Report (Burns, 1964). It also led to a strain study on the deformed pebble shapes (Burns and Spry, 1969), discussion on the origin of the deformed conglomerate (Spry and Burns, 1967), and petrofabric work on the quartz fabrics in the deformed conglomerates at Goat Island (Spry and Burns, 1972).

Australian Research Council (ARC) supported university research by David Gray in the period 1988-1989 enabled further detailed mapping of the coastal strip between Penguin and Leith and led to field guides (Berry et al., 1990; Berry and Gray, 2001). This mapping was also utilised in a subsequent Ar-Ar study by David Foster, David Gray and Catherine Spaggiari on the Forth Metamorphics (Foster et al., 2005).

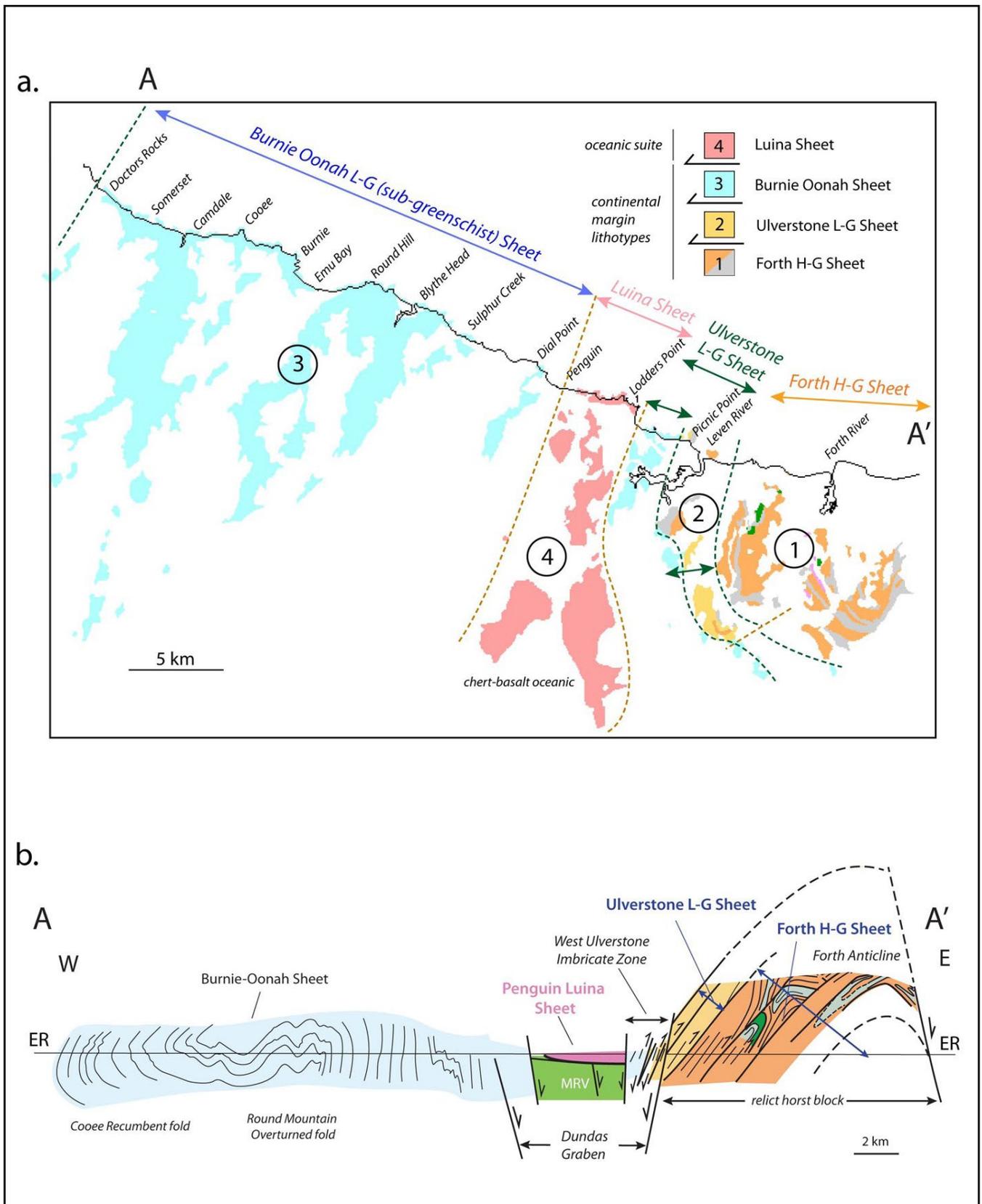


Figure 2. Simplified geological map of the north coast Proterozoic and Cambrian lithotectonic units (see Figure 1a for location). The north coast geology consists of stacked, subducted and exhumed continental margin segments including the Forth H-G Metamorphic Sheet, the greenschist facies L-G Ulverstone Metamorphic Sheet and the sub-greenschist facies Burnie Oonah Sheet. The uppermost sheet is an oceanic chert-basalt suite (Luina Sheet). b) Composite structural profile A-A' along the north coast from Wynard to Leith (see (a) for location). The profile includes the Gee (1977, fig. 3) Burnie structural profile on the west and an up-plunge projection of the Forth and Ulverstone Metamorphic sheets from the MRT 1:25,000 digital atlas on the east.

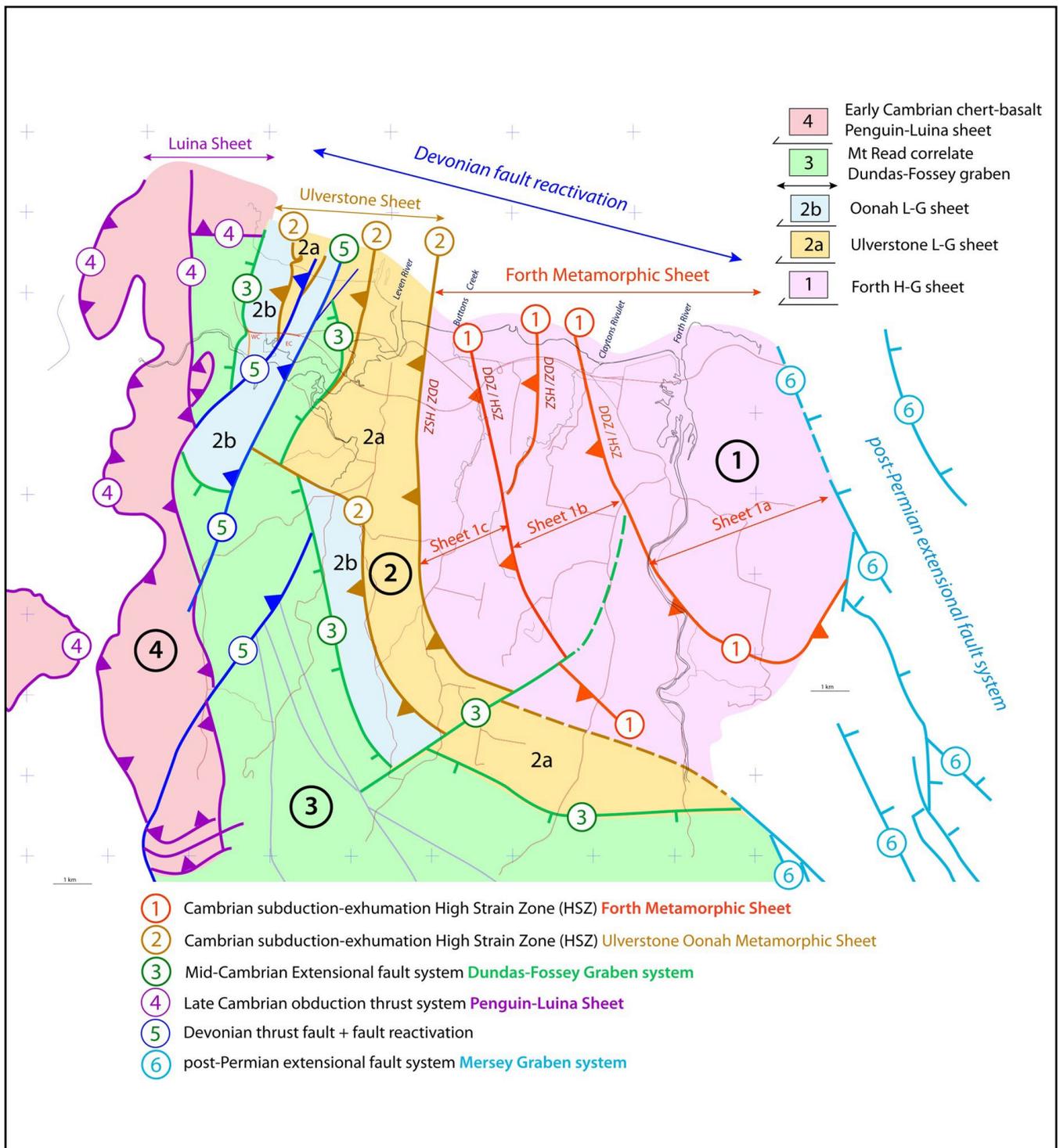


Figure 3. Lithotectonic sheet map showing the four major lithotectonic units (black circled numbers) and the associated complex fault network (coloured circled numbers). The lithotectonic units include the structurally lowest, H-G Forth Metamorphic Sheet (pink sheet/Unit 1), the overlying L-G Ulverstone Sheet (orange sheet/ Unit 2a), the L-G Oonah Sheet (blue sheet/ Unit 2b), the Cambrian volcanoclastic rift sequence of the Dundas-Fossey Graben (pale green/ Unit 3) and the structurally highest Cambrian chert-basalt sequence of the obducted Penguin-Luina sheet. The complex fault history from the oldest Cambrian subduction-exhumation high strain zones (HSZ) (red circled 1 faults) to the post-Permian extensional fault system (green circled 6 faults) is tabulated at the base of the figure.

The Forth Metamorphic Complex was further mapped and the structure and metamorphism defined as part of UTas BSc Honours project in 1991 by Rob Lewis (Lewis, 1991).

Geological Survey mapping was also undertaken by 1) David Seymour across the region as part of the MRT 1:25 000 mapping update, 2) David Seymour and Michael Vicary on the fault and broken formation zones

from Penguin to Picnic Point as part of the TasExplore Project (Seymour and Vicary, 2010), and 3) David Gray and Michael Vicary in 2013 as part of the Central North 3D Model Project.

Field observations collected by David Gray between 1976 and 2025 in the Ulverstone to Forth River area are presented in Gray (2025).



Figure 4. Google satellite images of the Ulverstone area coastline. a) Image showing the locations of geographic elements discussed in the text and the location and extent of the Ulverstone Metamorphic Sheet and the West Ulverstone Imbricate Zone. b) Image showing the positions of the major fault zones and lithology distribution.

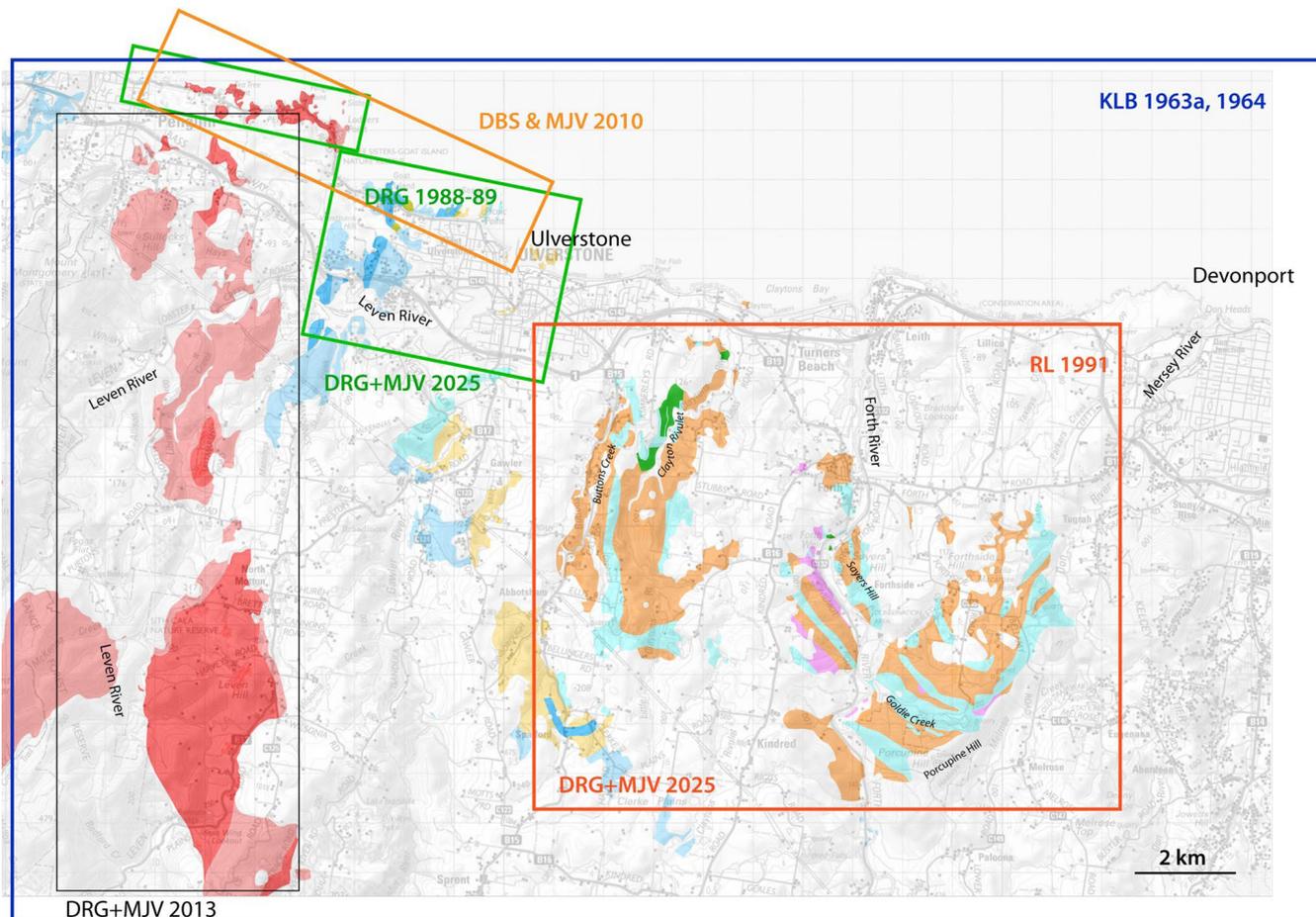


Figure 5. Mapping contributions to the Forth region are shown on a lithological map draped on a ListMap topographic base. Kerry Burns (KLB 1963a, 1964) mapped the area of the outer blue rectangle. Rob Lewis (RL 1991) mapped the Forth Metamorphic complex (red rectangle). David Gray (DRG1988-1989) mapped the coastal area between Penguin and East Ulverstone (green rectangles). David Seymour and Michael Vicary (DBS and MJV 2010) mapped the coastal fault and mega-breccia zones between Penguin and Picnic Point, West Ulverstone (orange rectangle). David Gray and Michael Vicary examined selected outcrops of the chert-basalt Luina Group correlates in the Penguin-Leven River area in 2013. David Gray and Michael Vicary field checked selected outcrops of the inland Forth Metamorphic Sheet and coastal exposures of the Oonah and Ulverstone Sheets in May, 2025.

## 2.2 Lithotectonic Units

The major, regional scale structural elements of the Ulverstone-Forth map area (Figure 3) include:

- a stacked series of metamorphic sheets including the high-grade Forth Metamorphic sheet of Mesoproterozoic protoliths (pink coloured Unit 1, Figure 3) overlain by the low-grade Ulverstone Metamorphic Sheet (orange coloured unit 2a, Figure 3) and the low-grade Oonah Sheet of Neoproterozoic protoliths (blue coloured Unit 2b, Figure 3) separated by higher strain shear zone interfaces.
- extensional faults bounding Middle Cambrian Dundas Fossey pull apart basin or graben (green coloured unit 3, Figure 3),
- a Late Cambrian oceanic thrust sheet (salmon pink unit 4, Figure 3) that consists of a Early Cambrian basalt-chert-sedimentary olistostrome sequence, with a basal fault shown by the heavy pink barbed line.

- a major Devonian anticline-syncline pair of the Abbotsham/Forth Anticline and Eugena Syncline (Figure 2b).
- a series of north-trending, west-dipping reverse faults along the western flank of the Devonian Forth Anticline (Figure 2b).
- northwest-trending post-Permian extensional faults bounding the Mersey pull-apart basin or graben (Figure 3).

## 3.0 THE ULVERSTONE METAMORPHIC SHEET

The structure of the Ulverstone Metamorphic Sheet is discussed within three outcrop domains. These are the superbly exposed coastal segments of 1) the eastern part as the Ulverstone Metamorphic Sheet proper, and 2) the western part as the West Ulverstone Imbricate Zone, and 3) the poorly outcropping inland part of the sheet (the orange area 2a, Figure 3).

### 3.1 The Coastal Segment: Picnic Point through to East Ulverstone Beach (Figures 4 and 6)

This segment is a homoclinal, west-dipping stack of structurally intercalated litho-tectonic units, including quartzite, schistose platy quartzite and quartz-mica schist with large erosional gaps of possible pelitic units (Figures 6 and 7). The quartzites occur as pod-like bodies, separated and bounded by mylonitic and schistose zones (Figure 7). Across the segment there are apparent domains in plunge direction of the mineral lineation  $L_m$  and mesoscopic folds (Figure 8). The mesoscopic folds show an overall S-fold vergence (looking down plunge). The largest pod at Seagull Islet is cored by a large-scale, isoclinal synform, with Z-asymmetric folds on the lower limb (east side) of the synform (Figure 9).

The Picnic Point wave-cut platform at low tide extending to Seagull Islet and the islands east of Seagull islet consists of quartzite macro-scale shear lozenges enveloped and cut by mylonitic quartzite, quartz-mica schist and mica-quartz schist (Figures 7, 10 and 11). These are the tectonic "fish" of Burns (1963a, 1964).

#### 3.1.1 Picnic Point Wave-cut Platform

The wave-cut platform at Picnic Point at low tide provides exposure of intensely deformed, interfingering lithologies within transposition layering where lithological boundaries

are sub-parallel to the dominant foliation ( $S_m/S_2$ ). These lithologies include tapering lenses of strongly deformed pebble conglomerate, mica-quartz schist, quartz-mica schist, mylonitic platy quartzite and phyllite enveloping lozenges of quartzite at varying scales (Figures 12, 13, 14 and 15). This tectonic package sits structurally above the Seagull Islet and Picnic Point quartzite macro-shear lozenges (see Sections 3.1.2 and 3.1.3). A series of quartzite shear lozenges or pods occur on the east side of the Point.

Interlayered mica schist, quartz-mica schist, deformed pebble conglomerate, and quartzite are deformed by kink bands of varying widths and sizes (Figures 11 and 16). A large, 30 m wide box fold dominates the structure on the western side of the outcrop (Figure 16). Dextral kinks have a NW-SE trend, whereas sinistral kinks have a NE-SW trend (Figure 16). Kink axes either plunge to the NW (dextral set) or the SW (sinistral set) or lie somewhere in between.

Many low angle contraction faults are transitional into kink band boundaries (KBB) along their lengths (Figure 11b). These faults are NNW-SSE trending, SW dipping curvilinear surfaces. At their northern terminations they are oblique to the N-S trending  $S_2$  foliation, but southwards swing into sub-parallelism with this foliation (Figure 11b).



Figure 6. Google satellite image of coastal outcrops that make up the Ulverstone Metamorphic Sheet. The outcrops are only exposed at low tide and extend from Picnic Point to East Ulverstone Beach. Large areas are covered by beach sand and recent sediment.

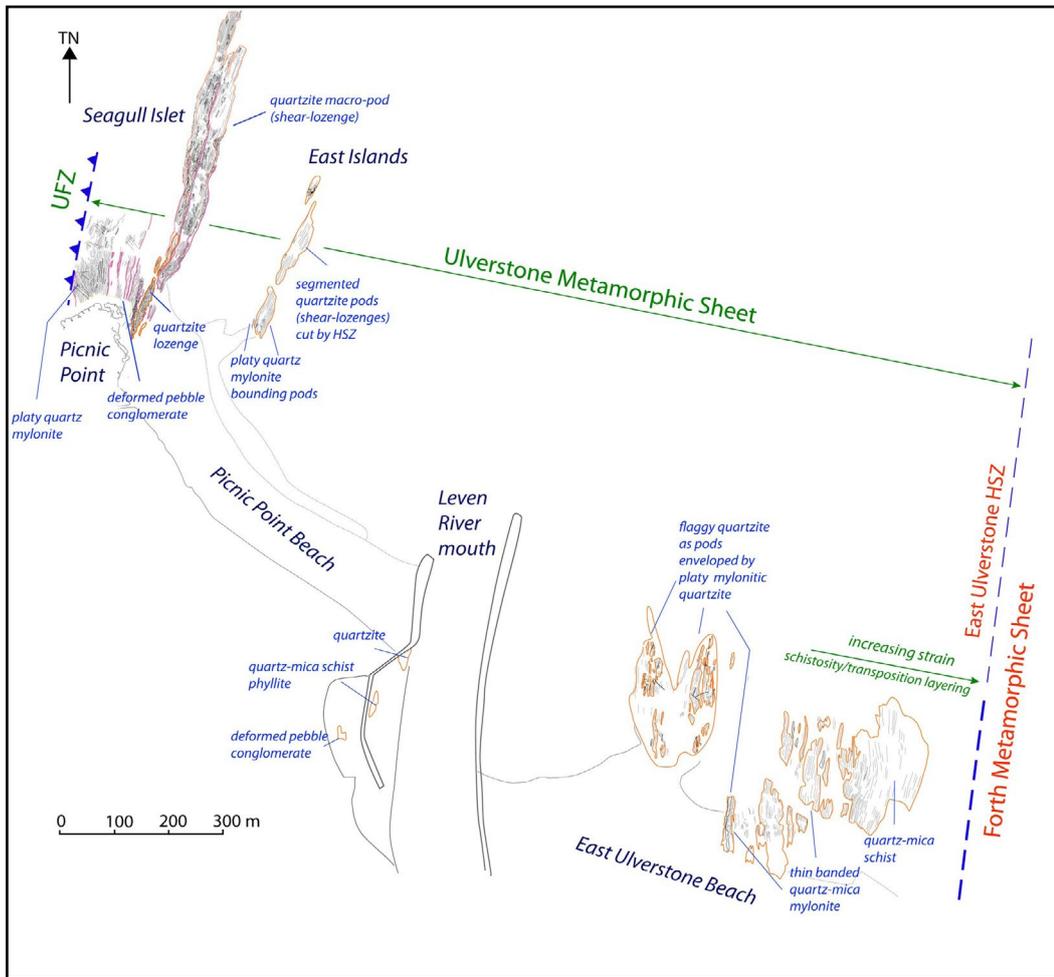


Figure 7. Simplified structural form line map of the Ulverstone Metamorphic Sheet from coastal outcrops consisting of tidal wave-cut platforms and islands from Picnic Point to East Ulverstone Beach. The islands both west and east of the Leven River mouth consist of erosional remnants of relict quartzite pods or macro-shear lozenges entrained within strongly deformed schist and pebble conglomerate.

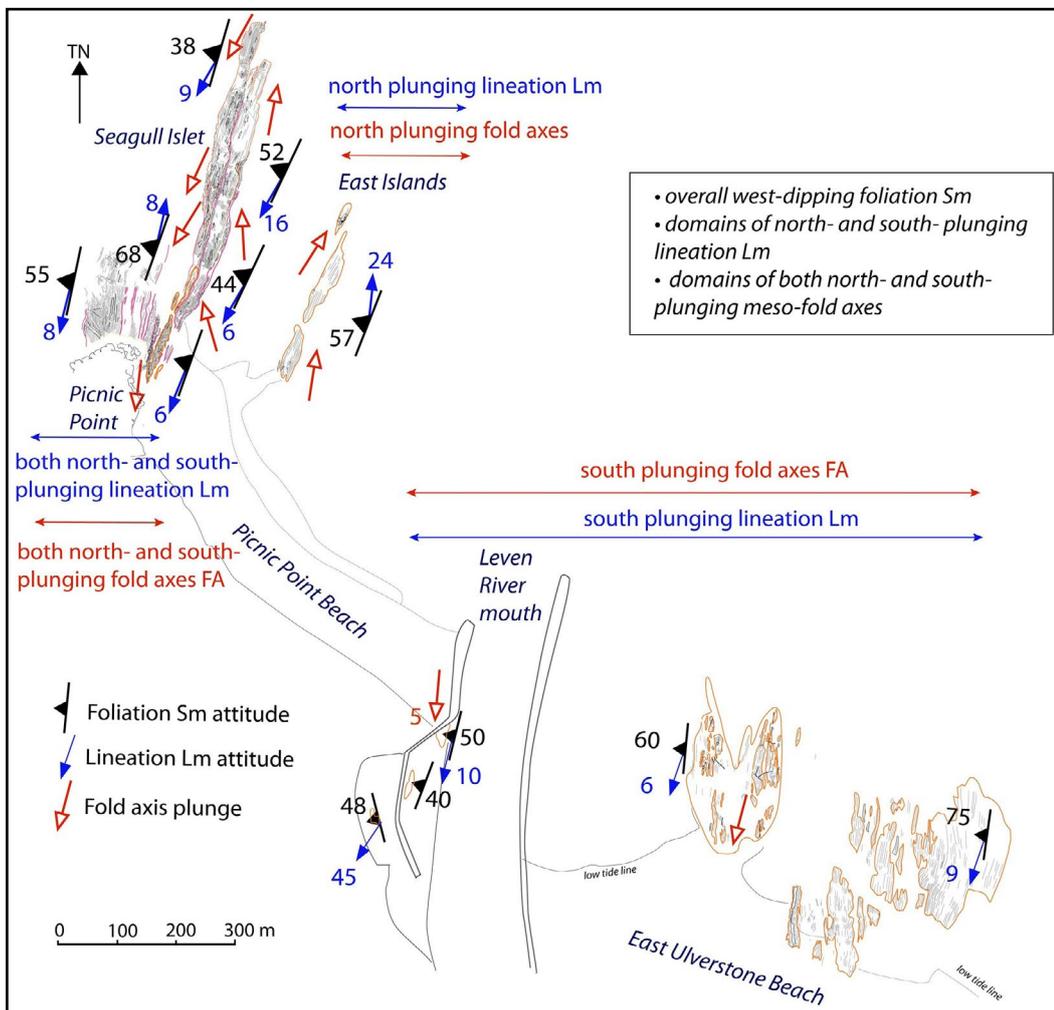


Figure 8. Simplified structural map of the Ulverstone Metamorphic Sheet based on structural data collected from the wave cut platforms exposed at low tide between Picnic Point and East Ulverstone. The map depicts domains of fold axis plunge and lineation plunge.

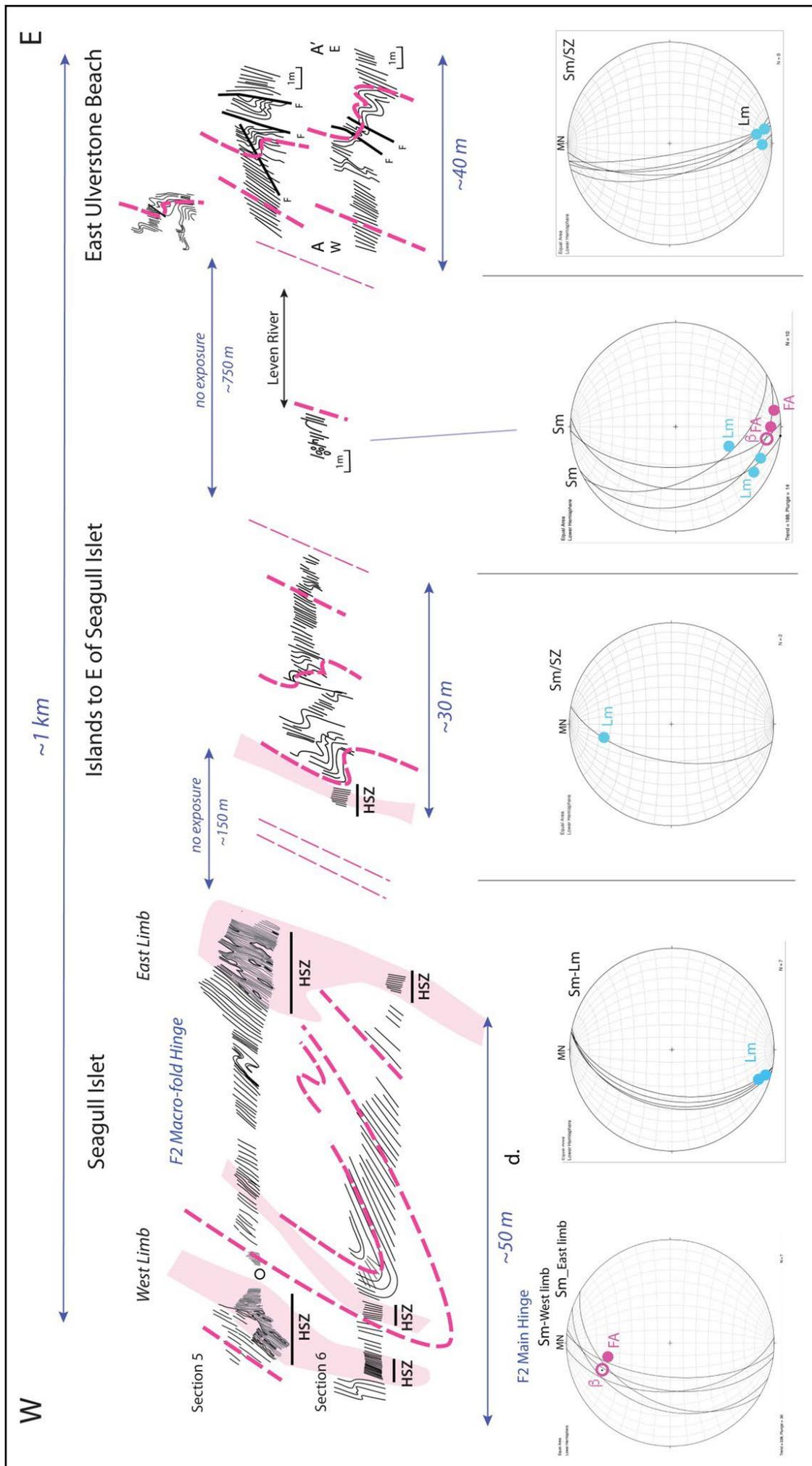


Figure 9. Structural profile from Picnic Point/Seagull Islet to East Ulverstone based on isolated, individual quartzite outcrop sections across the Seagull Islet macro-lozenge, the southernmost island east of Seagull Islet and the middle part of the low-tide outcrops at East Ulverstone Beach. Form lines in So/Sm are shown by the fine black lines, with the overall regional structure form lines shown by the heavy, pink dashed lines. The pink shading denotes areas of higher strain (HSZ) as shear zones of strongly to intensely foliated schistose quartzite and intercalated strongly foliated pelite. Note the large gaps in exposure between the outcrops (see Figure 7). The stereonets show the overall moderate to steep dip of the foliation Sm across the profile and the varying plunge direction of the lineation Lm (blue dots). The plunge of the Seagull Islet synformal macrofold is shown by the pink dot (measured fold axis) and pink circle (determined  $\beta$  axis).

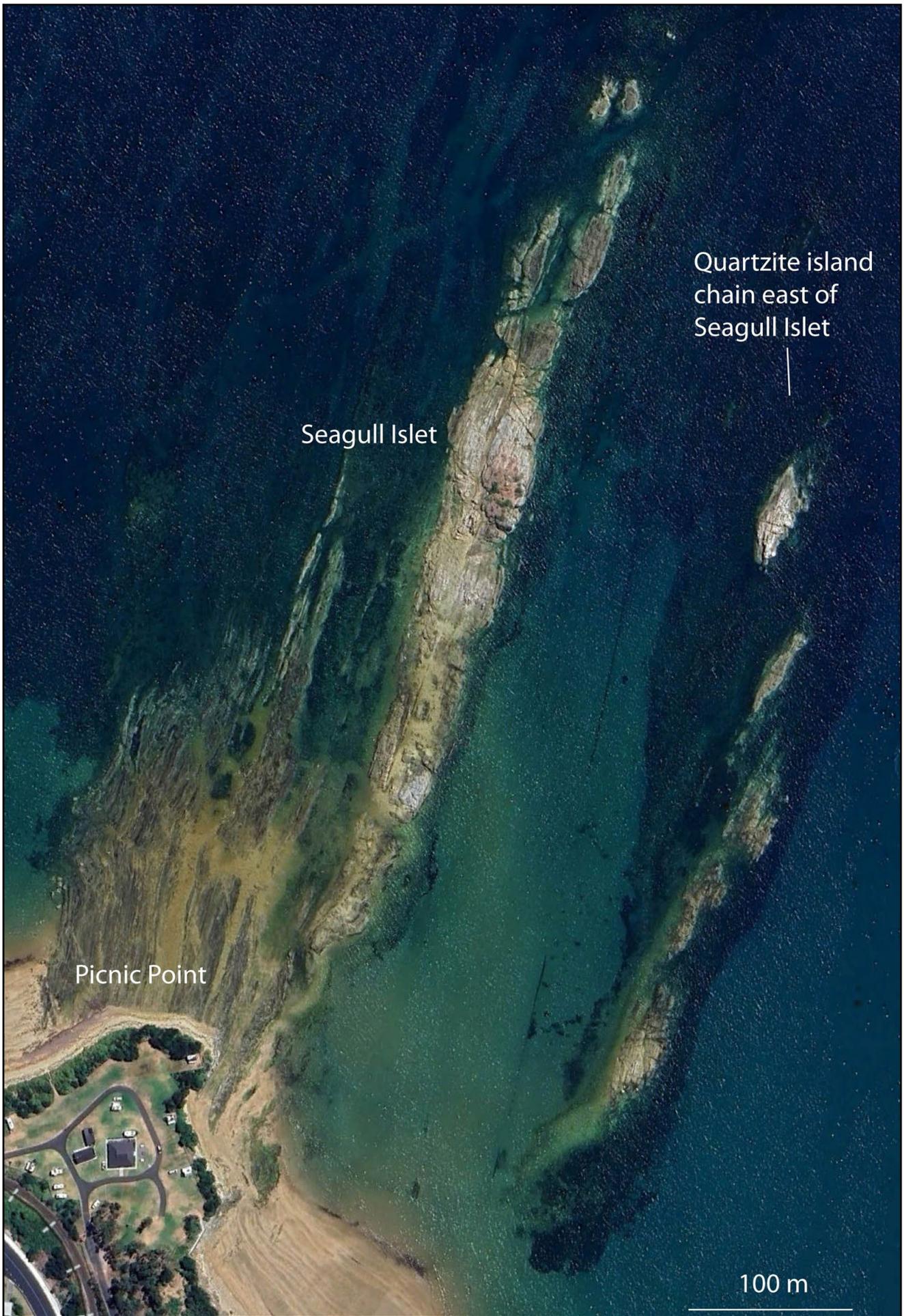


Figure 10. Google satellite image of the Picnic Point wave cut platform, the Seagull Islet quartzite train and the isolated quartzite islands east of Seagull Islet. These outcrops are at the top of the west dipping Ulverstone Metamorphic Sheet in the footwall of the Ulverstone Fault Zone (see Section 4.3.3). The Seagull Islet quartzite and the quartzite islands east of the Islet have pod-like form typical of macro-scale shear lozenges.

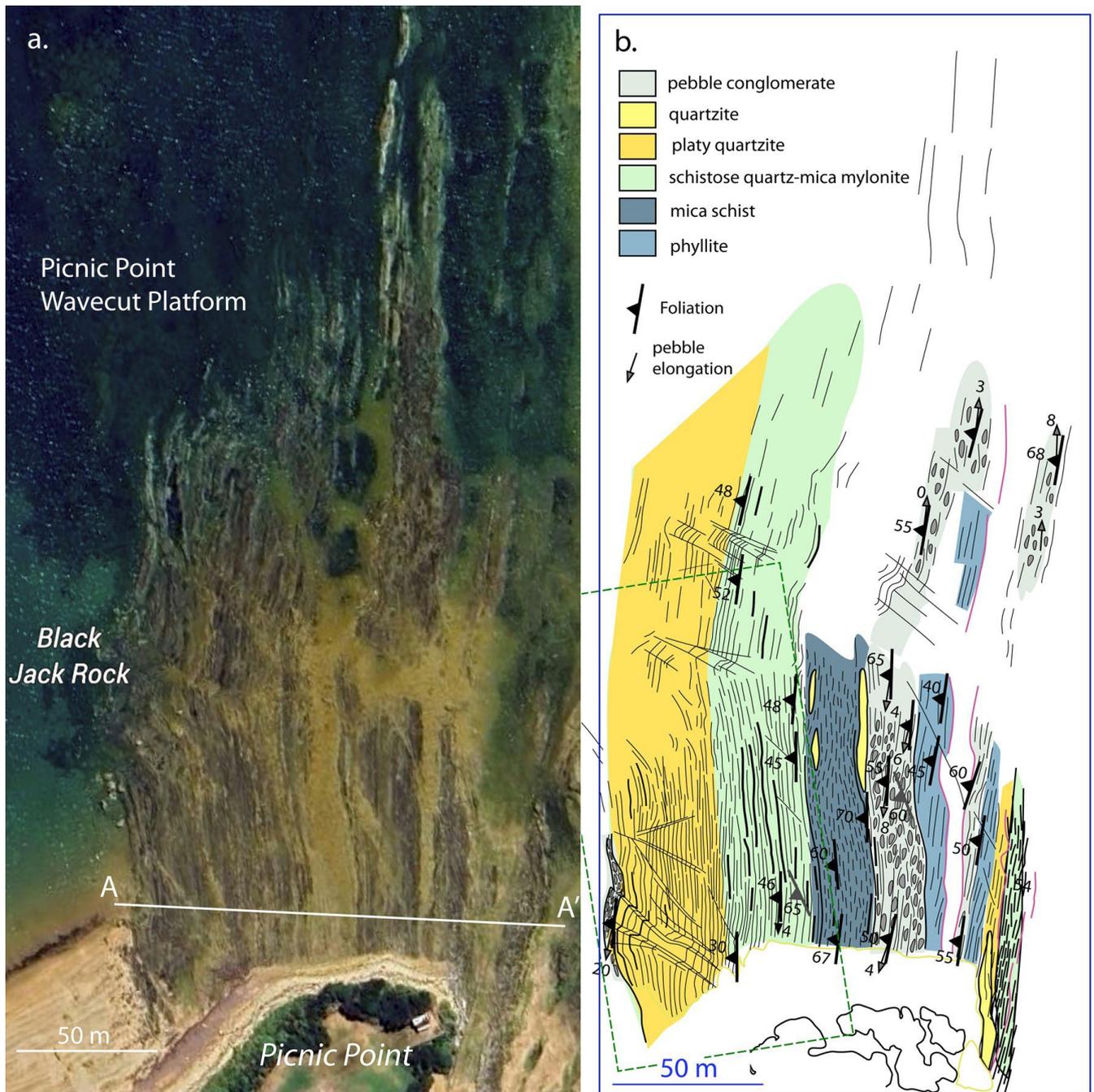


Figure 11. Picnic Point wave cut rock platform. a) Google satellite image of the Picnic Point wave-cut platform at low tide. The A-A' profile location for Figure 12 is shown. b) Lithotectonic structural map of the Picnic Point rock platform. The platform consists of intercalated schistose quartzite, quartz-mica schist, mica-quartz schist, pebble conglomerate and thin, discontinuous bands of quartzite (see Figures 13 and 14). The green dashed box is the region of large scale, late stage kinks that dominate the western side of the platform (see Figure 16 and Appendix B).

### 3.1.2 Seagull Islet Macro-scale Shear Lozenge

The Seagull Islet macro-shear lozenge is an elongated, pod-like quartzite body (Figures 7 and 10) with foliation  $S_m$  strike-parallel elongation, tapered terminations and an overall homoclinal west-dip (Figures 17, 18 and 19). The quartzite pod has an extrapolated length of  $\sim 620$  m and maximum width of 58 m at Seagull Islet knoll giving an X/Z aspect ratio of  $\sim 10:1$  in map view (Figure 19). The extrapolated length measurement assumes a pinched and tapered form, as at the south end, extending underwater

from the last outcrop at low tide (Figure 19). Comparison with a multiply boudinaged Goat Island deformed pebble or "tecton" (after Burns and Spry, 1969) with a similar X/Z shape ratio of  $\sim 10:1$  suggests that the macro-shear lozenge has a possible depth or Y extent of 93 m (see Figure 19b for explanation). It would have an egg shaped YZ profile (see pebble profiles, Figure 19b) where the quartzite pod is bounded and enveloped by mylonitic to schistose shear zones in all three dimensions (Figures 19 and 20). It is also infiltrated and segmented by these anastomosing shear zones (Figure 20).





Figure 13. View of the eastern side of the Picnic Point wave-cut platform at low tide with Seagull Islet knoll on the horizon middle right. The photograph shows transposed and structurally intercalated bands of pebble conglomerate (right foreground), quartz-mica schist (left foreground), and quartzite (photo middle left).

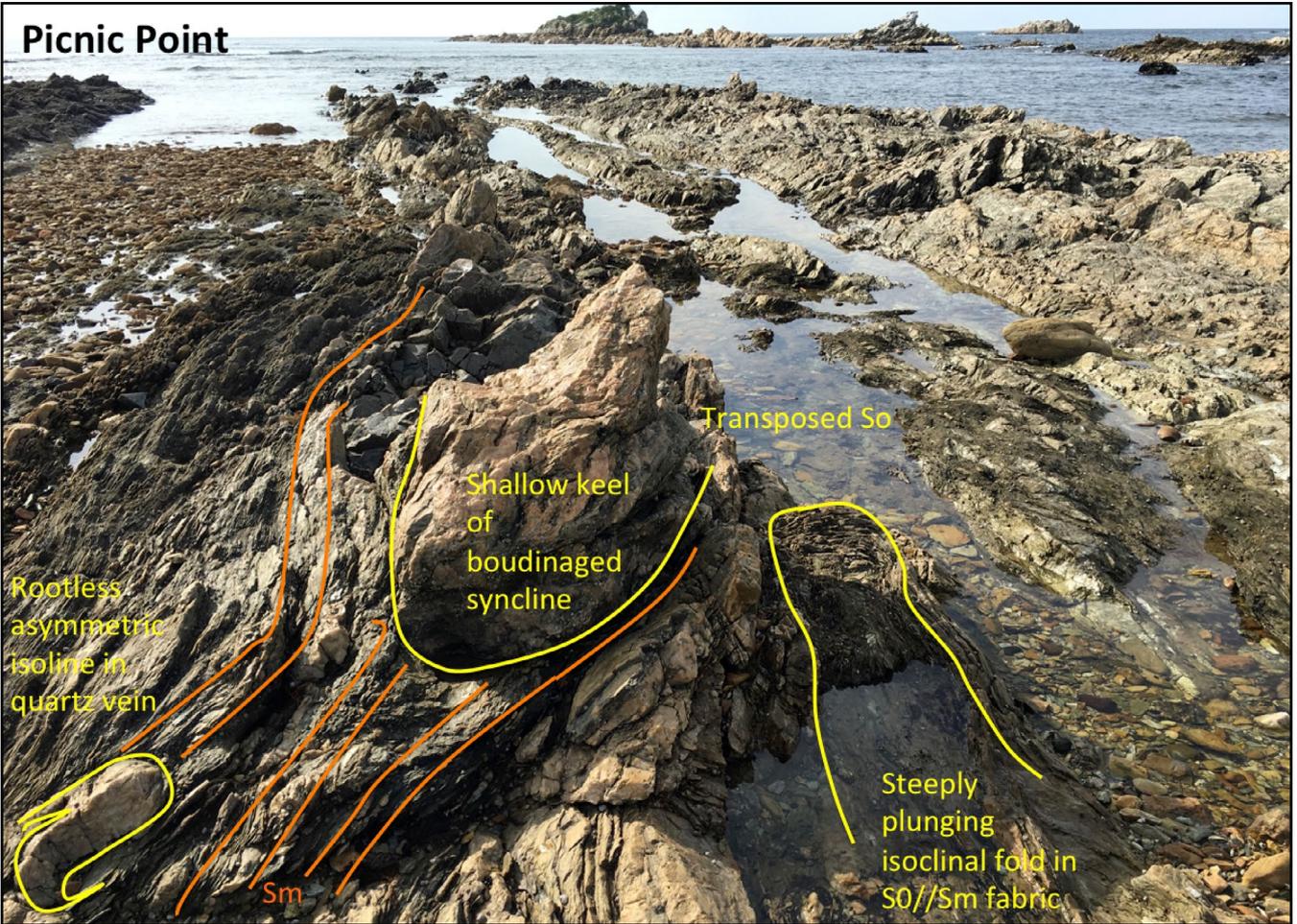


Figure 14. Relict synformal keel of quartzite enveloped by platy quartzite, quartz-mica schist and phyllite exposed in the shore platform at Picnic Point. Seagull Islet is on the horizon (mid-photo). This reflects a process of boudin segmentation of isoclinally folded quartzite layers leaving isolated synformal keels enveloped by the dominant foliation Sm (see Section 3.1.2).



Figure 15. Structurally intercalated phyllite, quartz-mica schist, mica-quartz schist and dismembered quartzite layer at the base of the smaller quartzite lozenge along the eastern edge of Picnic Point. This mylonitic quartz-mica schist also sits structurally above the west-dipping Picnic Point shear lozenge. View is looking to the south.

A summary of the structural elements and character of the Seagull Islet and Picnic Point macro-shear lozenges are provided in Figure 17. The Picnic Point shear lozenge (see Section 3.1.3) is the along-strike continuation and segmented southern part of the same quartzite body that makes up the Seagull Islet lozenge. The macro- and internal structural configuration of the Seagull Islet macro-shear lozenge is shown in a series of form line structural maps (Figures 17, 18, 19, 21 and 22), map and stereonet (Figures 23, 24 and 25), and structural profiles (Figures 26, 27, 28, 29 and 30).

In map view, from a maximum map width of ~58 m Seagull Islet knoll, the macro-lozenge tapers and thins both northwards and southwards to the terminations (Figures 18 and 19). The quartzite pod also shows thinned or pinched segments spaced at ~100 m, 60 m and 90 m from north to south. The thinned portions have asymmetry, suggestive of pinching by macro-scale shear band boudinage with sinistral sense (compare with Figure 19b). These incipient pod segments have approximate ~100 m length scales. To support this, small-scale sinistral sense shear bands are relatively common in the Picnic Point coastal wave-cut platform, and the islands east of Seagull Islet (Figures 17 and 18) have been interpreted as sinistral sense, macro-shear lozenges (see Section 3.1.4). Structural and  $S_0/S_m$  form line maps of the Seagull Islet macro-lozenge show:

1. A general northeast strike ( $020^\circ$  TN) and west dip of the foliation  $S_0/S_m$  (transposed layering) within the lozenge (Figures 17 and 18).
2. A generally gentle ( $<15^\circ$ ) southwest plunging mineral lineation  $L_m$  within  $S_m$  (Figures 18 and 21b).
3. A synformal macro-fold closure defining the southern termination of the lozenge (Figure 17), with an inclined plunging, approaching reclined geometry designated as F2 (Figure 25).
4. Folded zones exist throughout the quartzite macro-lozenge (Figures 21a) with domains of upright folding made up of north-northwest trending mesoscopic folds and north to north-northeast trending folds (Figure 22b).
5. Varying north or south plunge for the north-northeast fold set (Figure 21a) and a general northwest plunge for the north-northwest fold set (Figures 21a, 22 and 23).
6. The north-northeast fold set is dominant on the western macro-fold limb and in the macro-fold core (green trend lines, Figure 22b).
7. A centrally located, pod core of refolded early isoclinal recumbent folds (designated F1) folded by the sets of upright folds (designated F3).
8. A variation in  $FA \wedge L_m$  angular relationship from sub-parallel or at low angles on the structurally higher, overturned, western limb of the macro-fold to greater angular separation ( $15^\circ$ - $30^\circ$ ), with a general clockwise rotation sense of FA towards  $L_m$ , on the structurally lower eastern limb (Figure 21b).

# West Side Picnic Point wave-cut platform

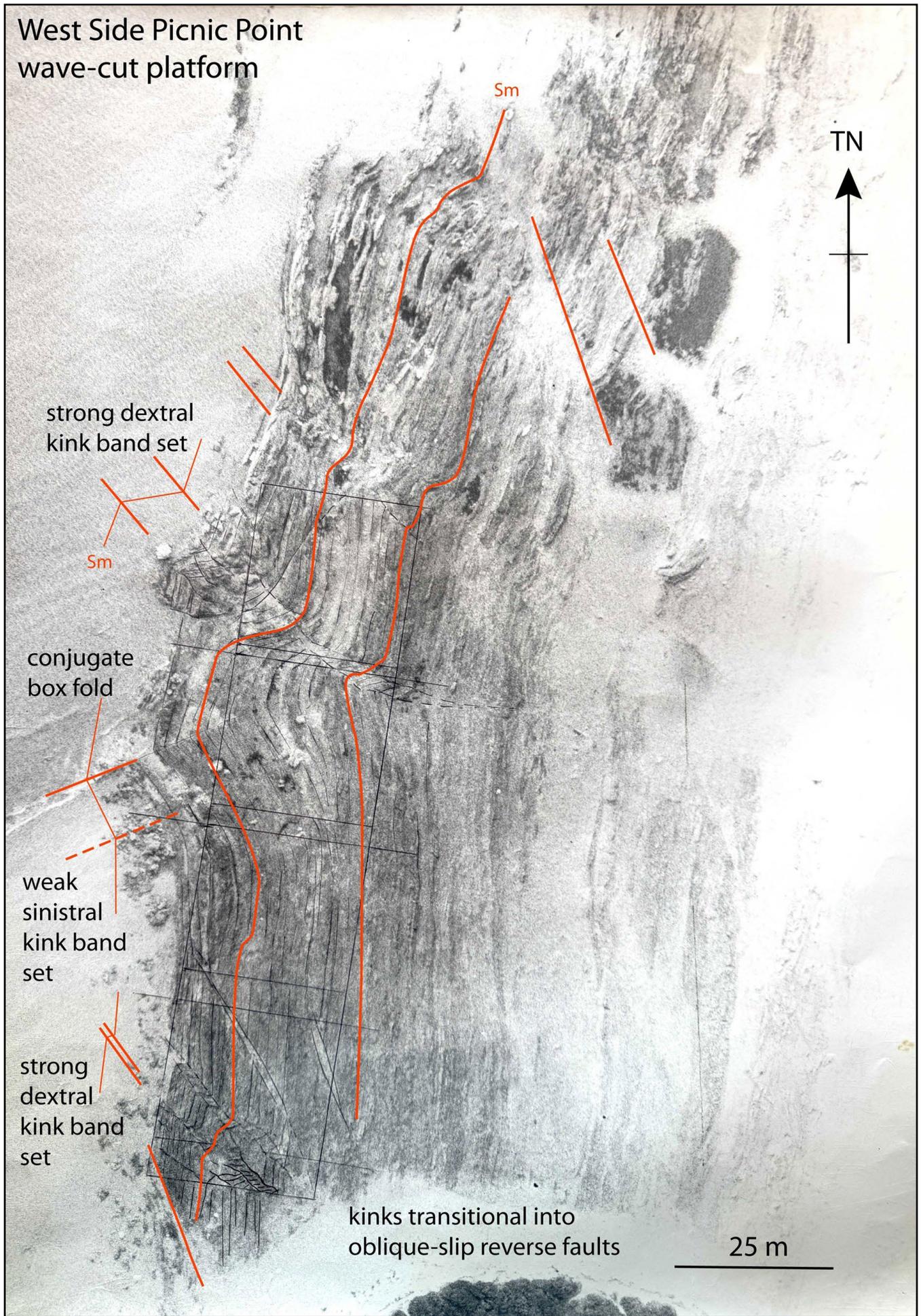


Figure 16. Kink band-related, large-scale box fold in foliated, platy, mylonitic quartzite on the western edge of the Picnic Point wave cut platform. The platform is a dominated by a northwest-trending dextral kink band set with poor development of the conjugate, east-northeast trending sinistral set (see Appendix B for kink data).

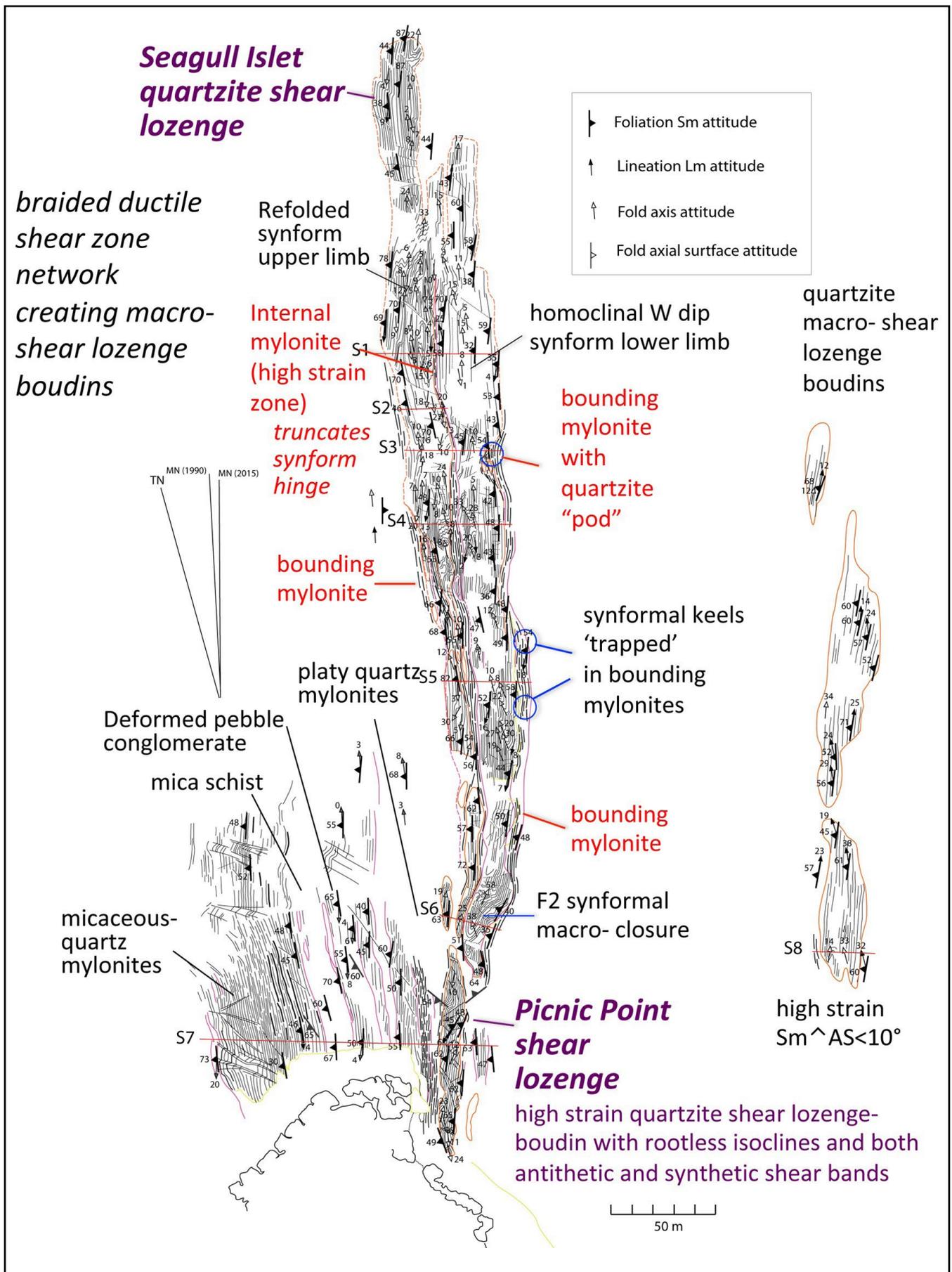


Figure 17. Structural summary map of the Picnic Point wave cut platform, the Seagull Islet and Picnic Point quartzite macro-shear lozenges, and the islands east of Seagull Islet. The summary map shows form line traces in  $So/Sm$  (thin black line traces), foliation  $So/Sm$  dip/strike attitudes, lineation  $Lm$  attitudes (black headed arrows) and the bounding mylonite zones (red line traces). A major F2 synform bounded by the high strain zones occupies the core and southern termination of the Seagull Islet macro-lozenge.

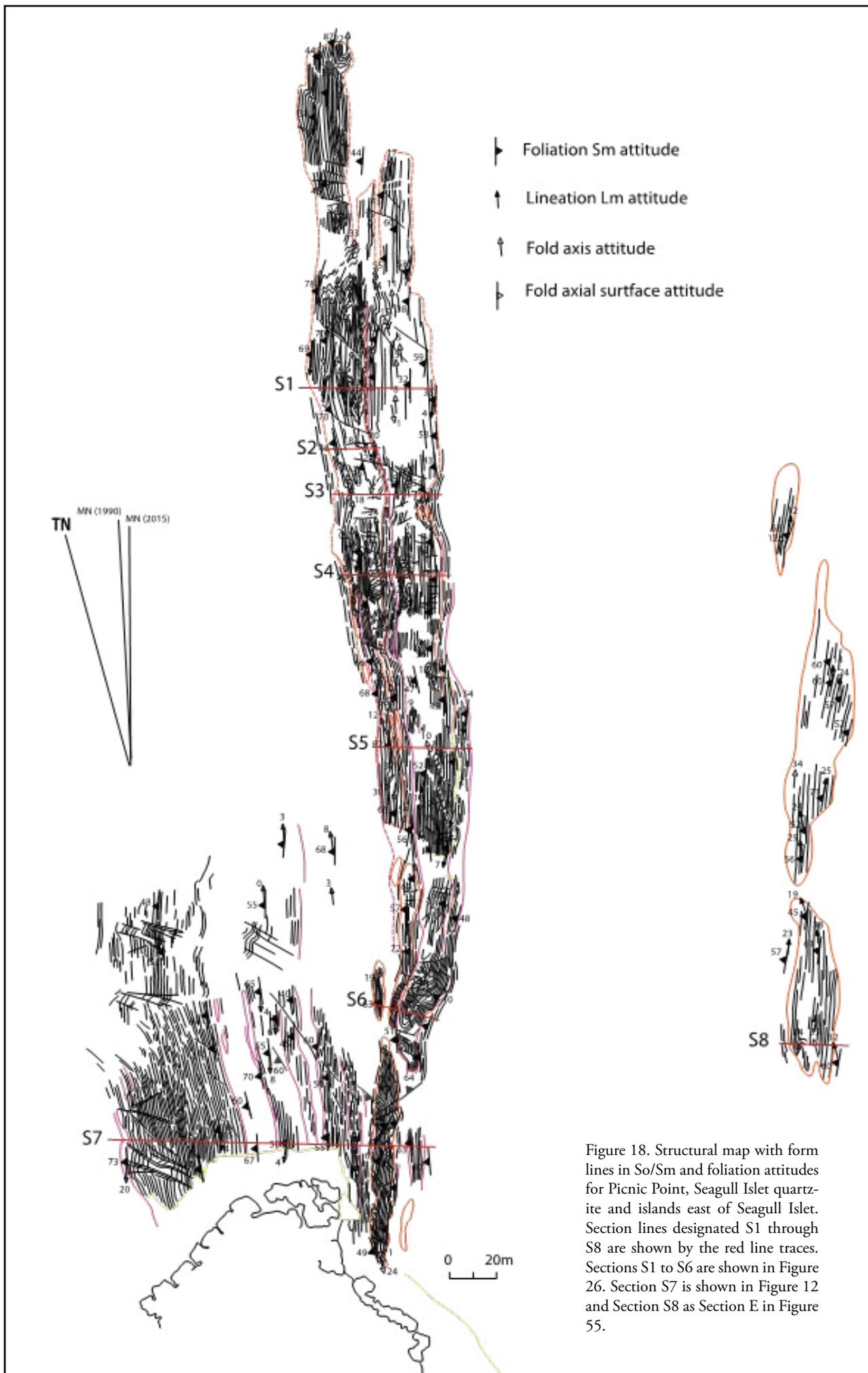


Figure 18. Structural map with form lines in  $S_0/S_m$  and foliation attitudes for Picnic Point, Seagull Islet quartzite and islands east of Seagull Islet. Section lines designated S1 through S8 are shown by the red line traces. Sections S1 to S6 are shown in Figure 26. Section S7 is shown in Figure 12 and Section S8 as Section E in Figure 55.

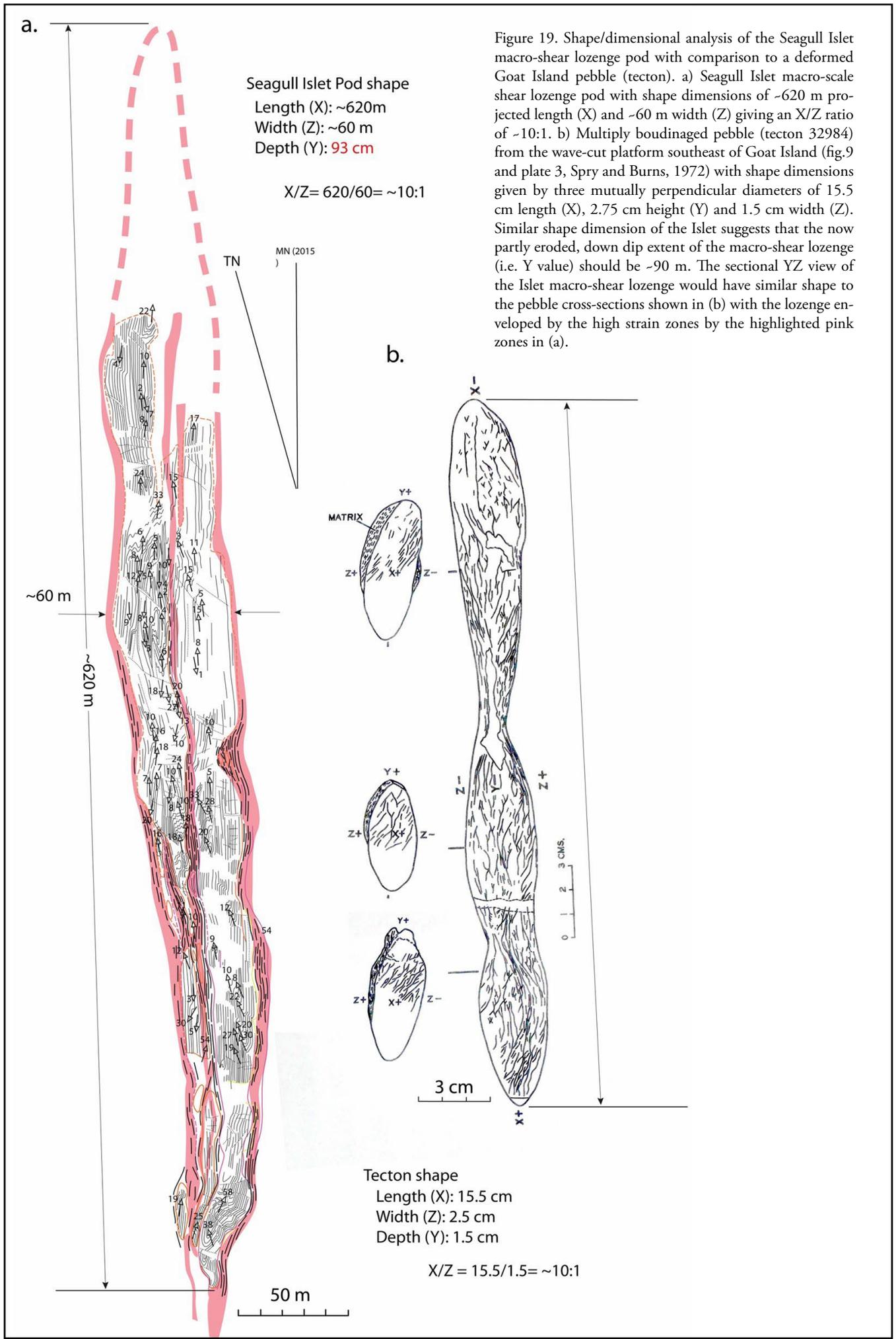


Figure 19. Shape/dimensional analysis of the Seagull Islet macro-shear lozenge pod with comparison to a deformed Goat Island pebble (tecton). a) Seagull Islet macro-scale shear lozenge pod with shape dimensions of ~620 m projected length (X) and ~60 m width (Z) giving an X/Z ratio of ~10:1. b) Multiply boudinaged pebble (tecton 32984) from the wave-cut platform southeast of Goat Island (fig.9 and plate 3, Spry and Burns, 1972) with shape dimensions given by three mutually perpendicular diameters of 15.5 cm length (X), 2.75 cm height (Y) and 1.5 cm width (Z). Similar shape dimension of the Islet suggests that the now partly eroded, down dip extent of the macro-shear lozenge (i.e. Y value) should be ~90 m. The sectional YZ view of the Islet macro-shear lozenge would have similar shape to the pebble cross-sections shown in (b) with the lozenge enveloped by the high strain zones by the highlighted pink zones in (a).

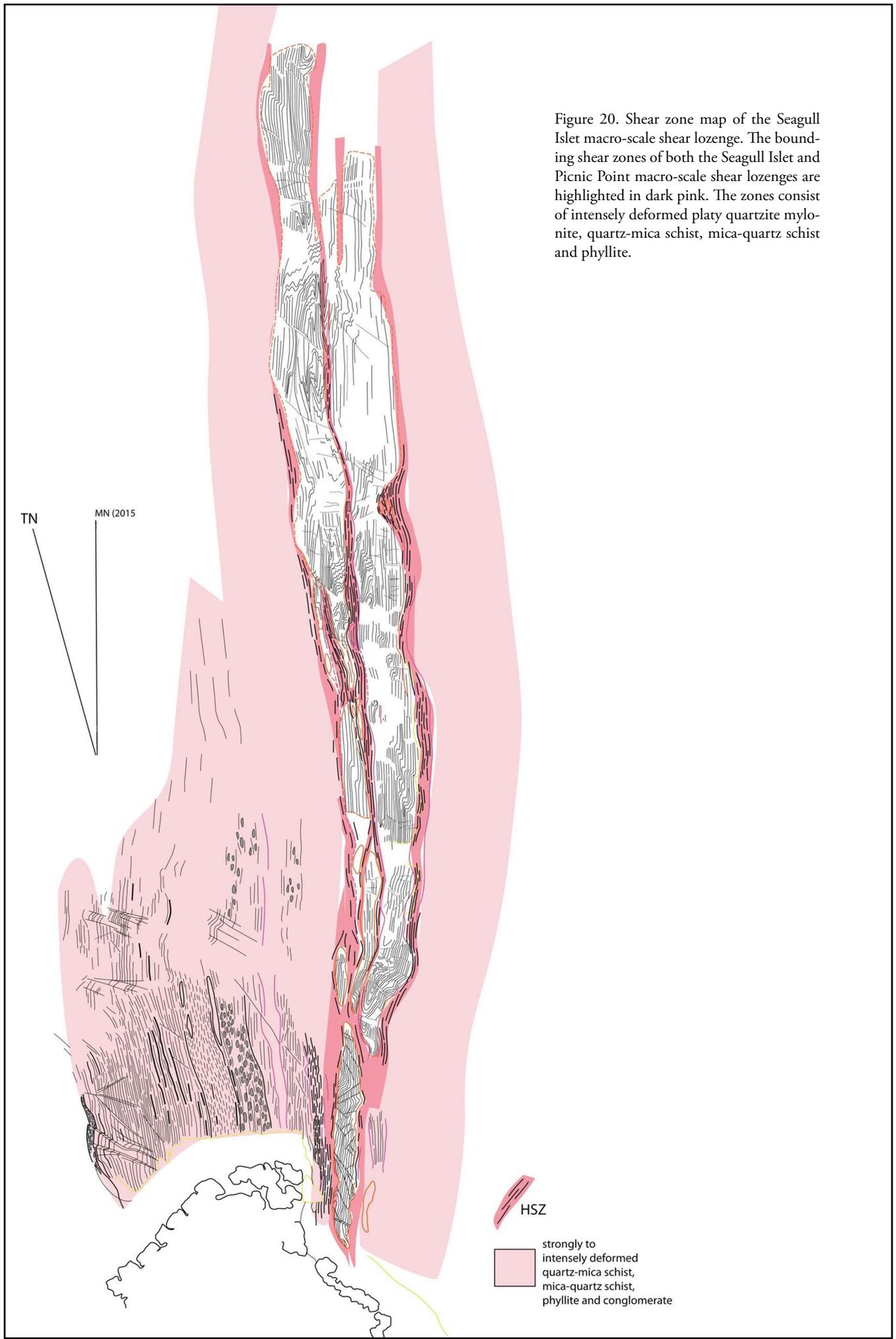


Figure 20. Shear zone map of the Seagull Islet macro-scale shear lozenge. The bounding shear zones of both the Seagull Islet and Picnic Point macro-scale shear lozenges are highlighted in dark pink. The zones consist of intensely deformed platy quartzite mylonite, quartz-mica schist, mica-quartz schist and phyllite.

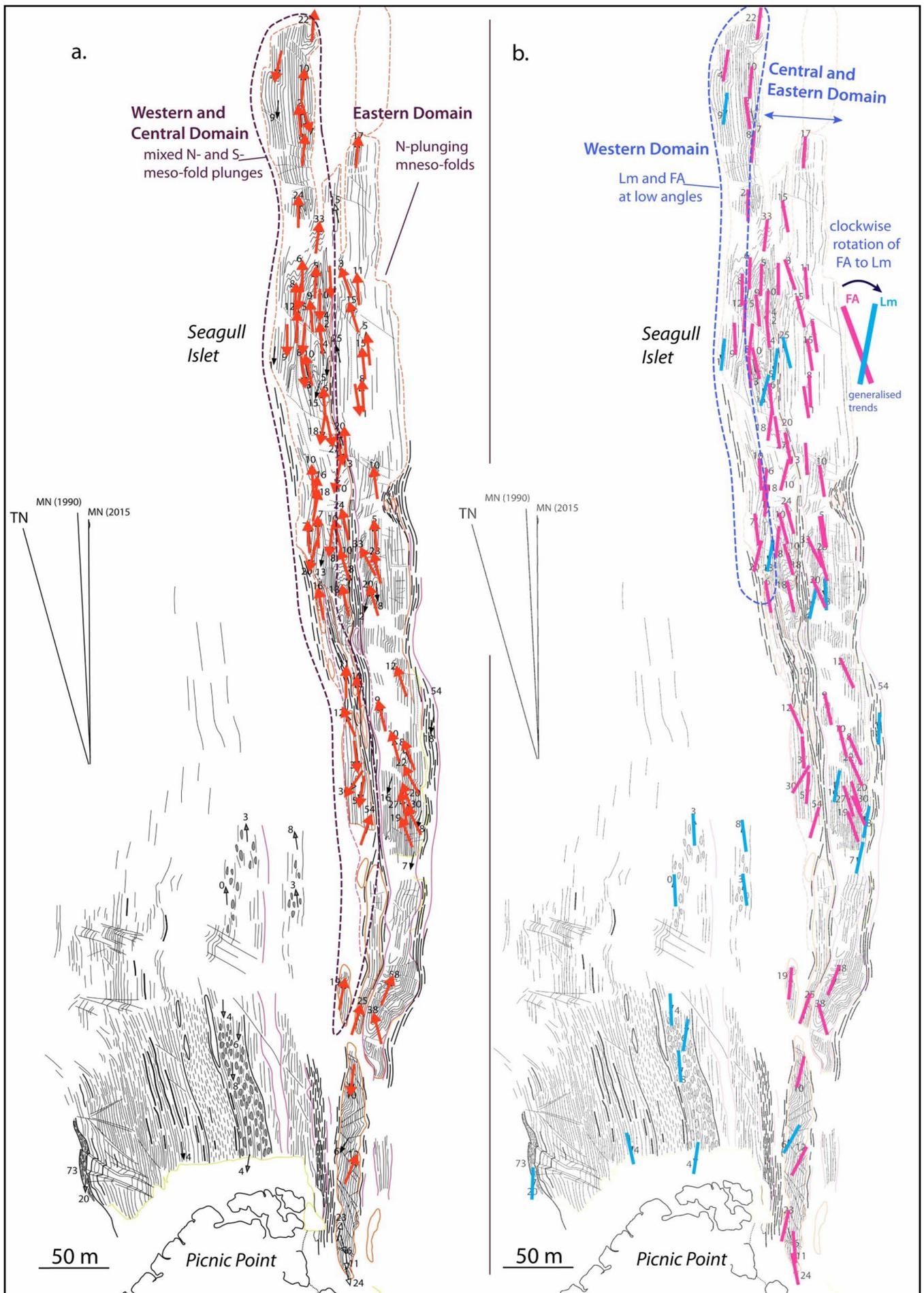


Figure 21. Picnic Point and Seagull Islet macro-lozenge structural summary maps. a) Fold axis (FA) plunge direction summary map. b) Fold axis (FA) (pink trend lines) and lineation (Lm) (blue trend lines) summary trend map.

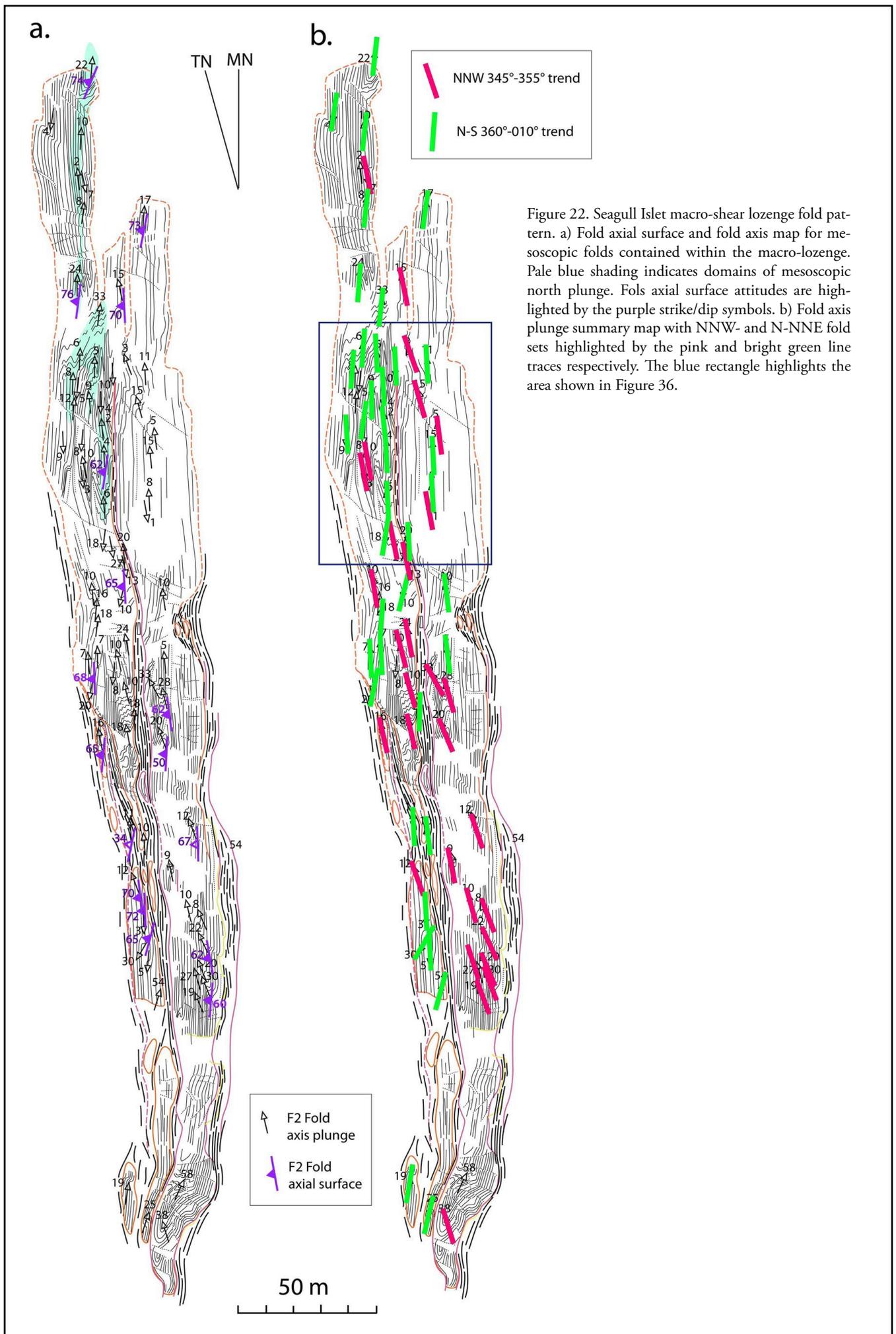


Figure 22. Seagull Islet macro-shear lozenge fold pattern. a) Fold axial surface and fold axis map for mesoscopic folds contained within the macro-lozenge. Pale blue shading indicates domains of mesoscopic north plunge. Folds axial surface attitudes are highlighted by the purple strike/dip symbols. b) Fold axis plunge summary map with NNW- and N-NNE fold sets highlighted by the pink and bright green line traces respectively. The blue rectangle highlights the area shown in Figure 36.

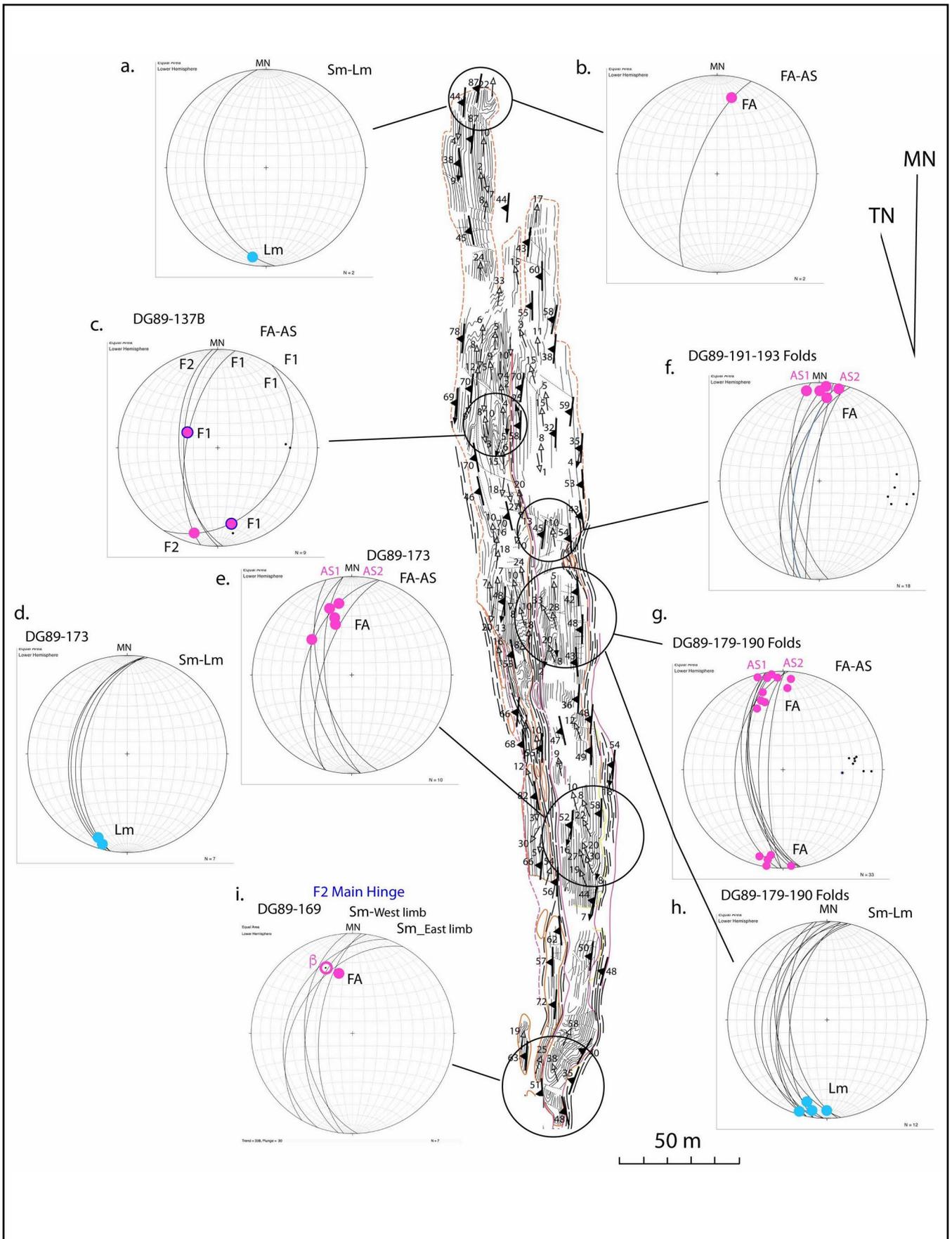


Figure 23. Seagull Islet quartzite lozenge with stereonets showing foliation Sm, lineation Lm and fold axis axial surface (AS) data at different points along the lozenge. Blue dots: lineation Lm attitudes. Pink dots: fold axis (FA) attitudes.

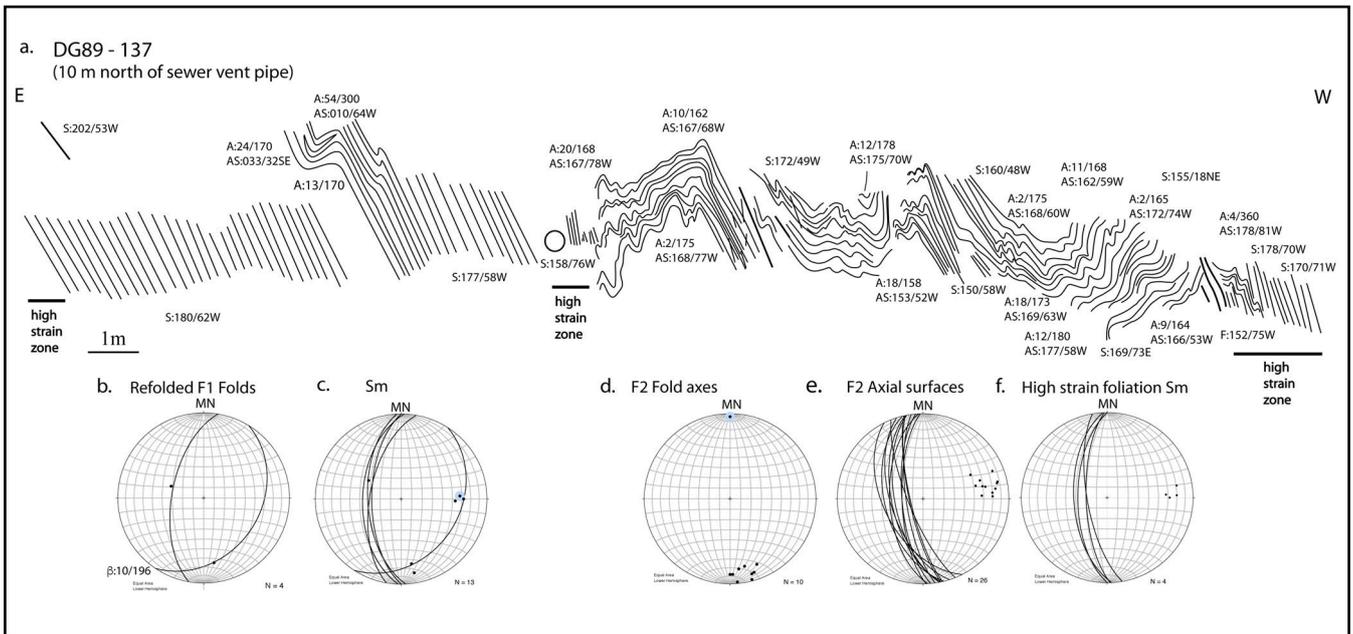


Figure 24. Northern structural profile across Seagull Islet. Note the view is looking south. a) Structural profile with structural data (readings are magnetic). b), c), d), e) and f) are stereonets of structural data collected in the profile.

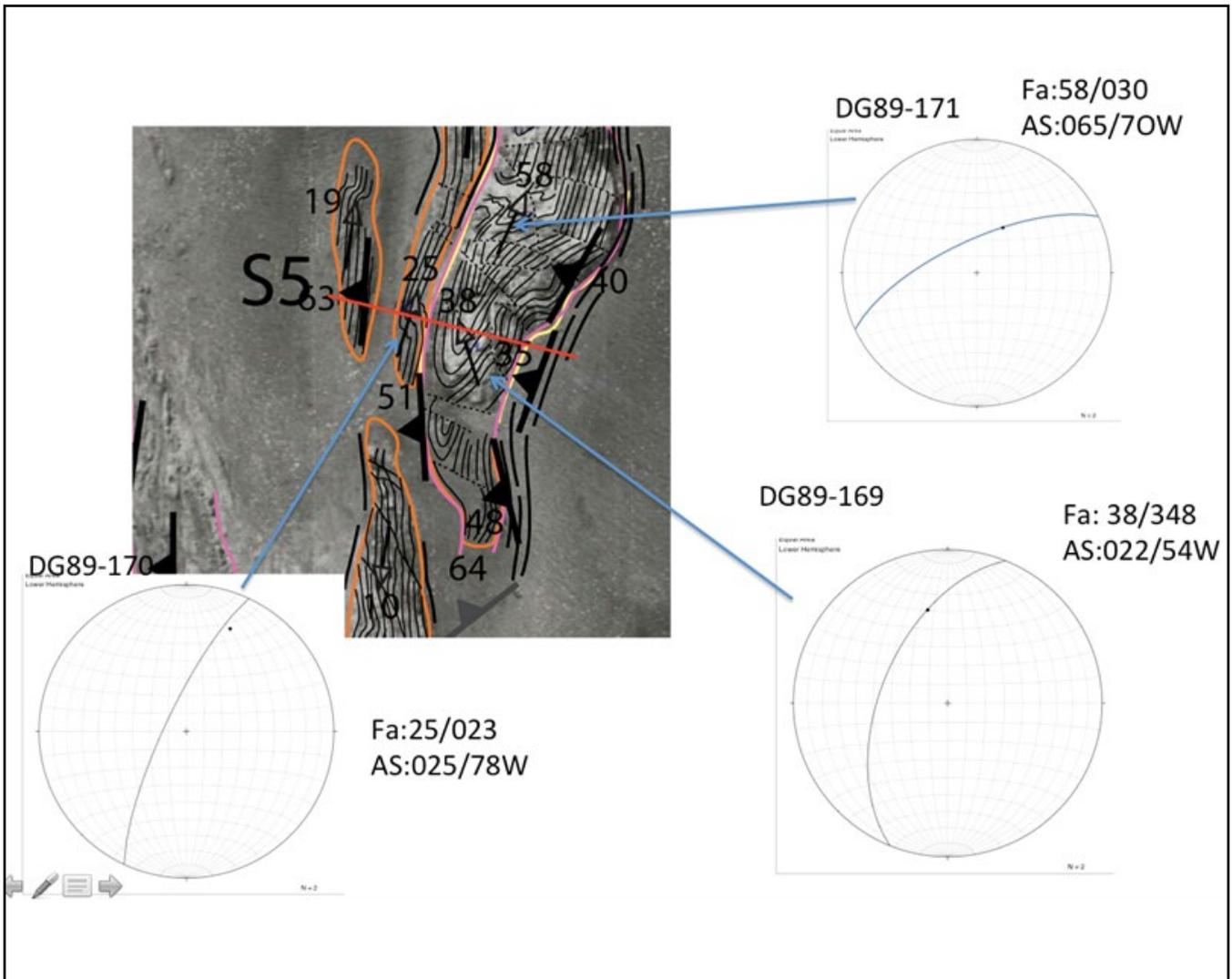


Figure 25. Form line map of the fold nose region of the major Seagull Islet F2 synformal fold with inset stereonets showing the attitudes of mesoscopic F2 fold axial surfaces (AS) and fold axes (FA).

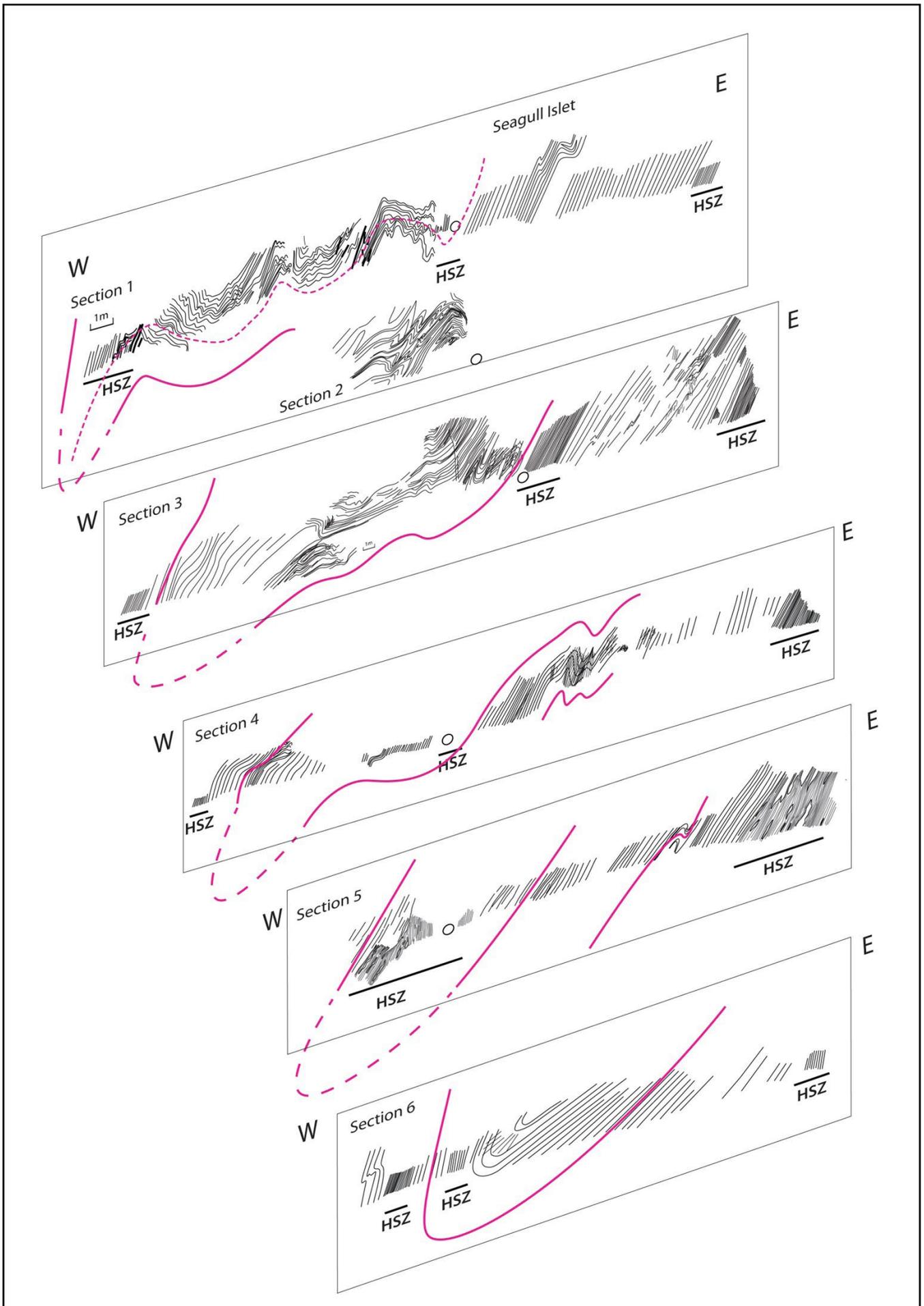


Figure 26. Stacked, sketch structural profiles across the Seagull Islet Quartzite macro-lozenge from north (Section 1) to south (Section 6). See Figure 18 for section locations. Compare with photo profiles in Figures 27, 28, 29 and 30.



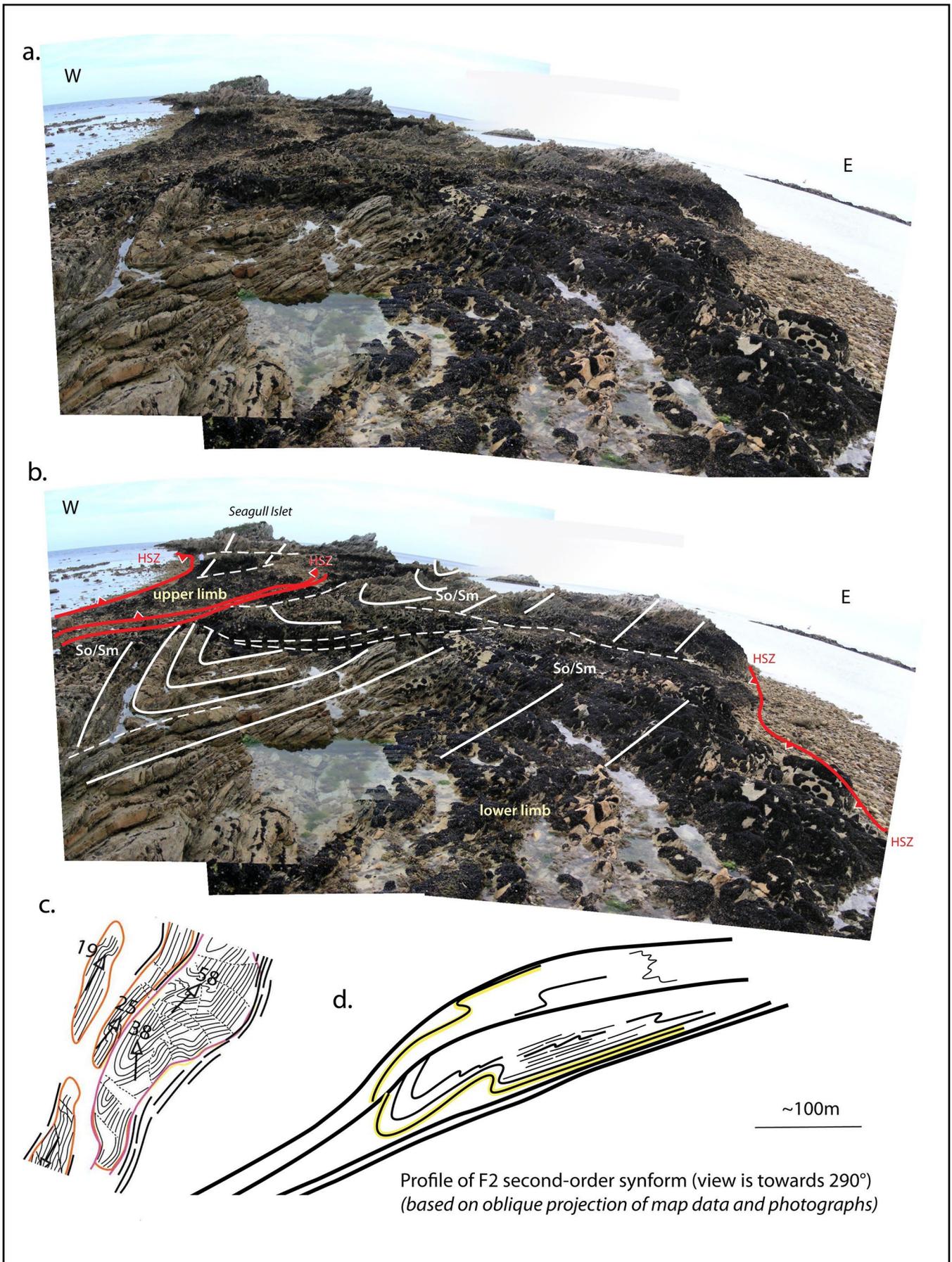


Figure 28. Profile of the Seagull Islet F2 synformal macro-fold bounded and cut by shear zones. a) Non-annotated photograph (Profile P6). b) Structural interpretation of the photograph in (a) showing form lines in So/Sm (white line traces), brittle faults (dashed white line traces) and boundaries of shear zones (red line traces). c) Map segment of the F2 macro fold hinge at the southern termination of the Seagull Islet quartzite lozenge. Arrows are local F2 fold plunges. d) Schematic F2 synformal macro-fold profile based on an oblique projection of map data and the outcrop photographs. The view is towards 290°.



Figure 29. Photo profiles P4 and P5 across the central part of the Seagull Islet quartzite lozenge. The upper photo profile P4 can be seen in the top part of the lower photo profile P5. Note the apparent homoclinal west dip through the quartzite lozenge and the strain variations through the lower profile shown by the thinner bedded form (middle left of photo), the flaggy nature of the quartzite (photo right) and the asymmetric Z-vergent mesoscopic F2 folds (photo centre bottom). Marked thinning of the quartzite layering can be seen across the Z-vergent asymmetric fold (middle bottom of photo).

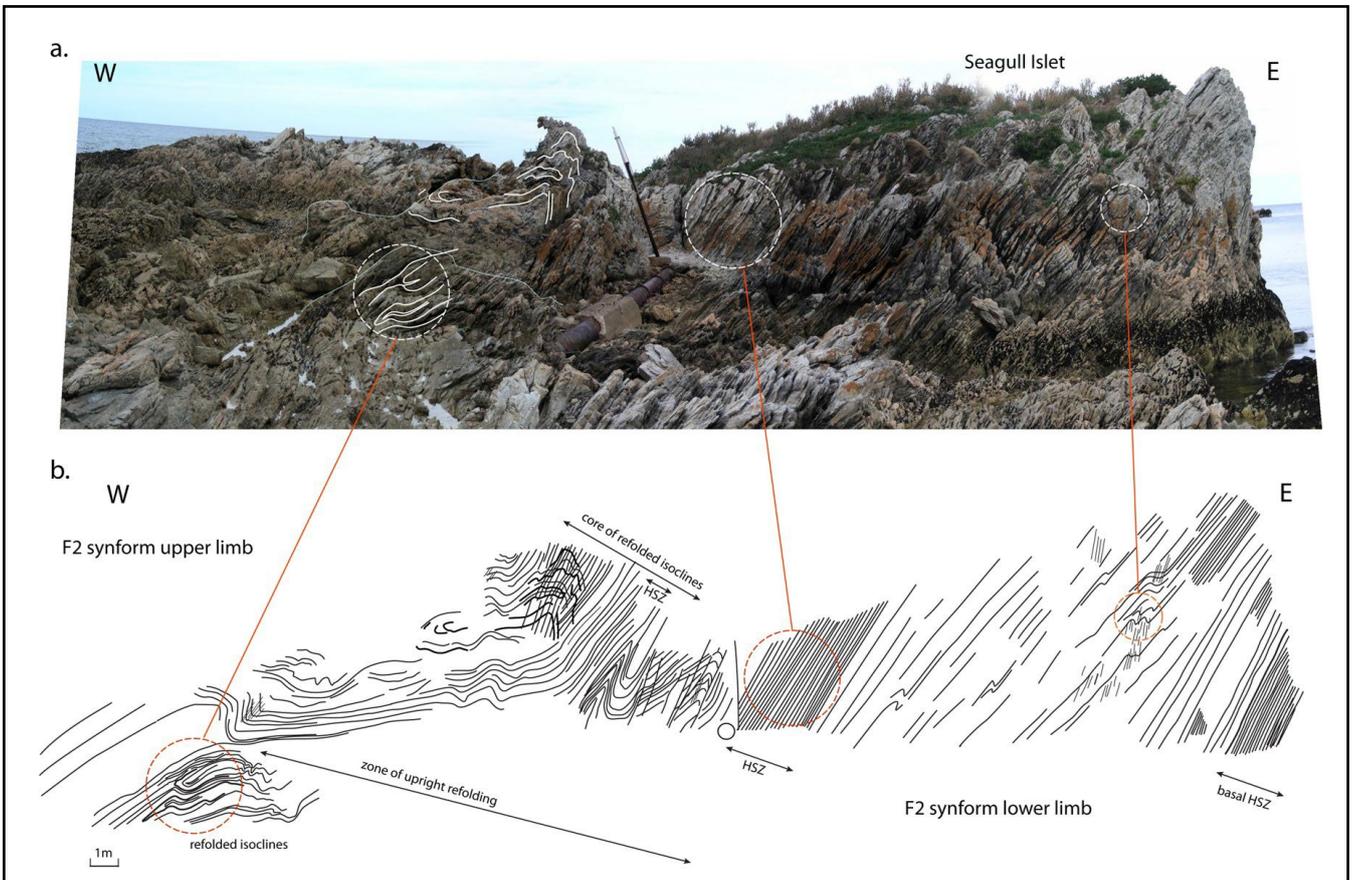


Figure 30. Profile through the northern part of the Seagull Islet macro-lozenge just south of the Islet. a) Annotated stitched photo profile (Profile P3) showing refolded early mesoscopic-isoclines in the core of the F2 synform. b) So/Sm form line interpretation of profile P3 showing an overall homoclinal west dip, penetrating high strain zones consisting of paty quartzite mylonite and banded phyllite, and a refolded core of mesoscopic, recumbent isoclinal folds that delineate the hinge zone of the major F2 synform.

The structural character of the Seagull Islet changes along strike from the south where there is a distinct synformal F2 fold hinge (Figure 25) enveloped by high strain zones of platy quartzite, quartz mica schist and pelite (Figures 20, 23, 27 and 28). Northwards this transitions into an apparent homoclinally dipping sequence punctuated by high strain zones (Figures 29 and 30) and a core of upright refolding (Figure 24) that refold small-scale, early recumbent isoclinal folds (Figures 30 and 31). The quartzite changes from an overall thin-bedded character to areas of platy, schistose quartzite that develop into the high strain mylonitic zones that transect the macro-shear lozenge (Figures 29 and 30). Geometrically the core of the Seagull Islet macro-lozenge is a synformal macro-fold with an inclined plunging, approaching reclined, geometry (Figures 25, 26, 27 and 28).

In profile, the macro-lozenge shows along strike changes in geometry from the apparent taper of the southern, synformal macro-fold nose (Section 6, Figure 26) to the segmented northern end, north of the Islet knoll where the actual termination is under water. Northwards the macro-fold loses fold-character to a less distinct, west-dipping, homoclinal form without a distinct hinge zone (Sections 4 and 5, Figure 26). The hinge region here has been transected or cut by shear zones (HSZ in Sections 3, 4 and 5, Figure 26). Just south of the sewer vent, in the north-central portion, the hinge is marked by a ~10 m zone of refolded, early recumbent, isoclinal mesoscopic folds (Sections 2

and 3, Figure 26). In the very northern profile (Section 1, Figure 26) the homoclinal west-dip is interrupted by a series of upright antiforms and synforms that dominate the western part of the profile over a distance of 15 m (Figure 24). These are compound folds made up of superimposed obliquely intersecting north-northwest and north to north-northeast trending fold sets (Figure 22b). The central antiform does however refold some rare, mesoscopic isoclinal recumbent folds suggesting that the F2 macro-fold hinge occurs in this position, along strike from the refolded fold stack at the sewer vent (Figures 30, 31, 32 and 33).

Within the Seagull Islet quartzite pod there are four sets of folds each with distinct size scale, axial surface and fold axis trends. These fold sets include:

1. The large-scale F2 tight to isoclinal synformal macro-fold that occupies the southern termination (Figures 27 and 28).
2. Small-scale mesoscopic F1/F2 recumbent isoclinal folds within the central-northern apparent core of the F2 macro-fold (Figures 30, 31 and 32).
3. 1-2 metre scale generally north-northwest plunging folds with axial surface strikes of 345°-355° (Figures 34, 35 and 36).
4. 1-2 metre scale variably north or south plunging folds with axial surface strikes of 360° to 010° (Figures 36 and 37).

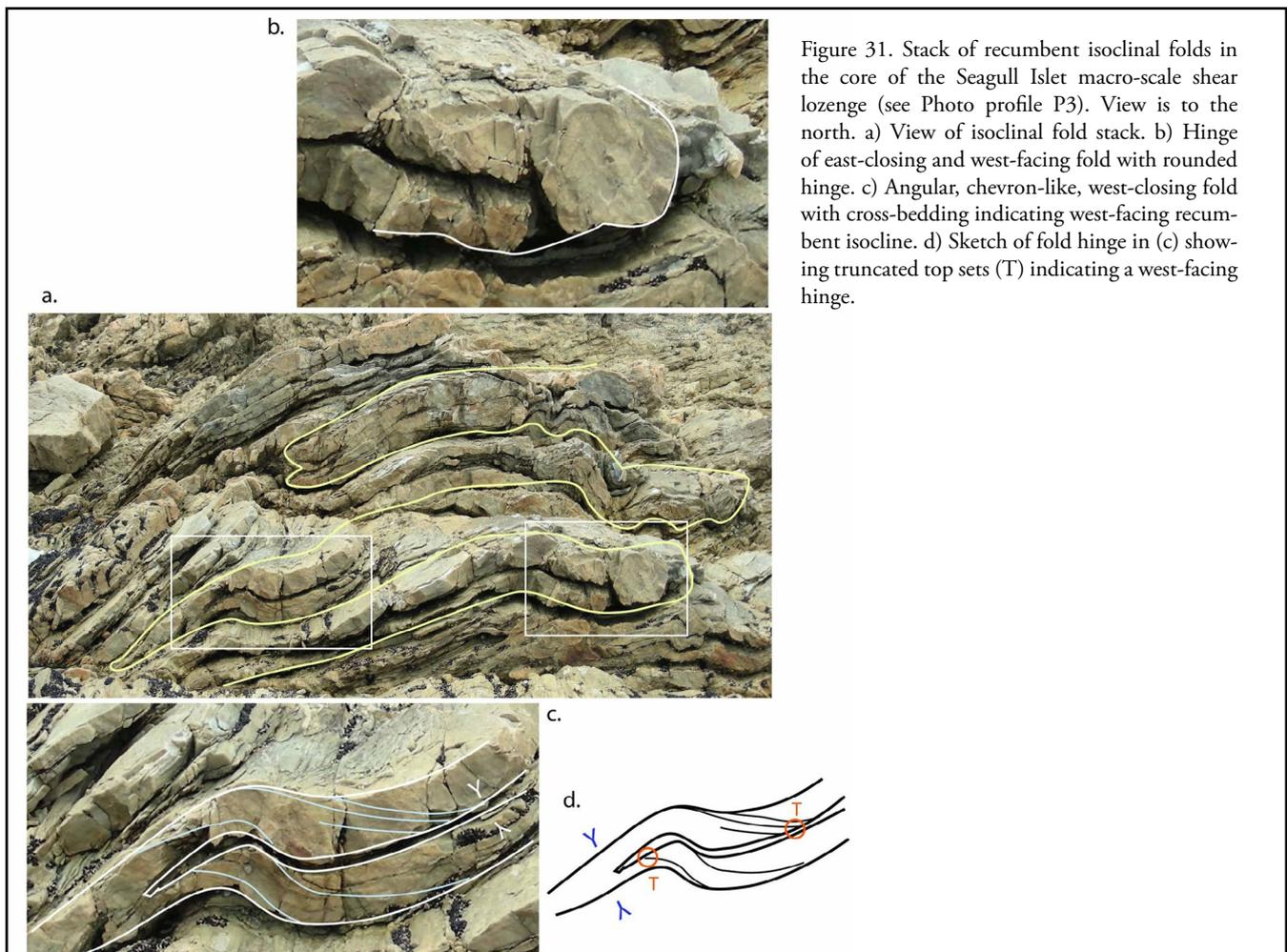


Figure 31. Stack of recumbent isoclinal folds in the core of the Seagull Islet macro-scale shear lozenge (see Photo profile P3). View is to the north. a) View of isoclinal fold stack. b) Hinge of east-closing and west-facing fold with rounded hinge. c) Angular, chevron-like, west-closing fold with cross-bedding indicating west-facing recumbent isocline. d) Sketch of fold hinge in (c) showing truncated top sets (T) indicating a west-facing hinge.

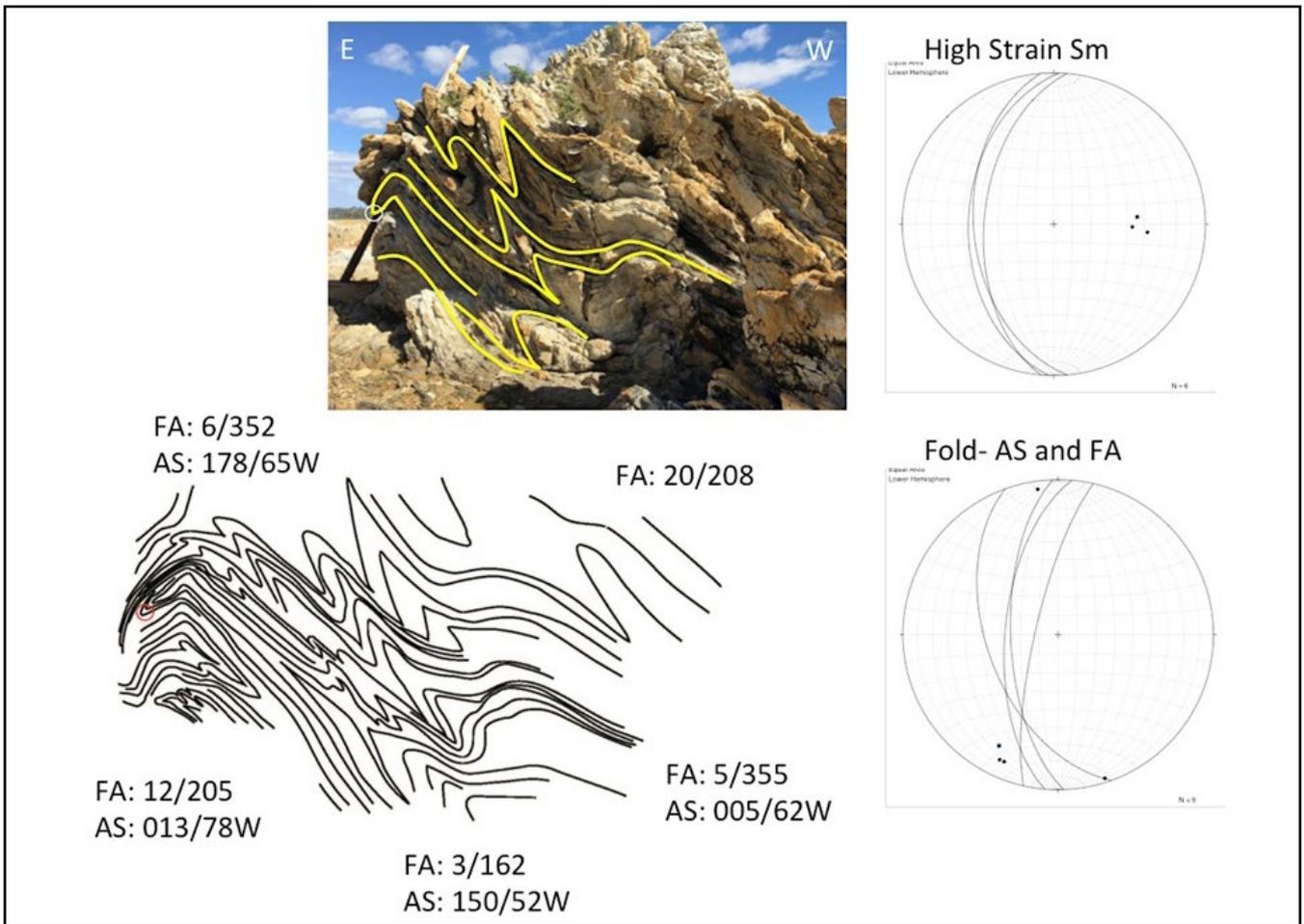


Figure 32. Refolded F2 mesoscopic isoclinal folds in the Sewer vent fold stack. a) Profile view of stack looking to the south with form lines in So/Sm as the yellow line traces. b) Complete sketch profile based on the photograph in (a). Fold axis (FA) and axial surface (AS) attitudes are magnetic. The red circle in centre left of the profile is the refolded hinge of the fold with curved hinge line shown in Figure 33c.

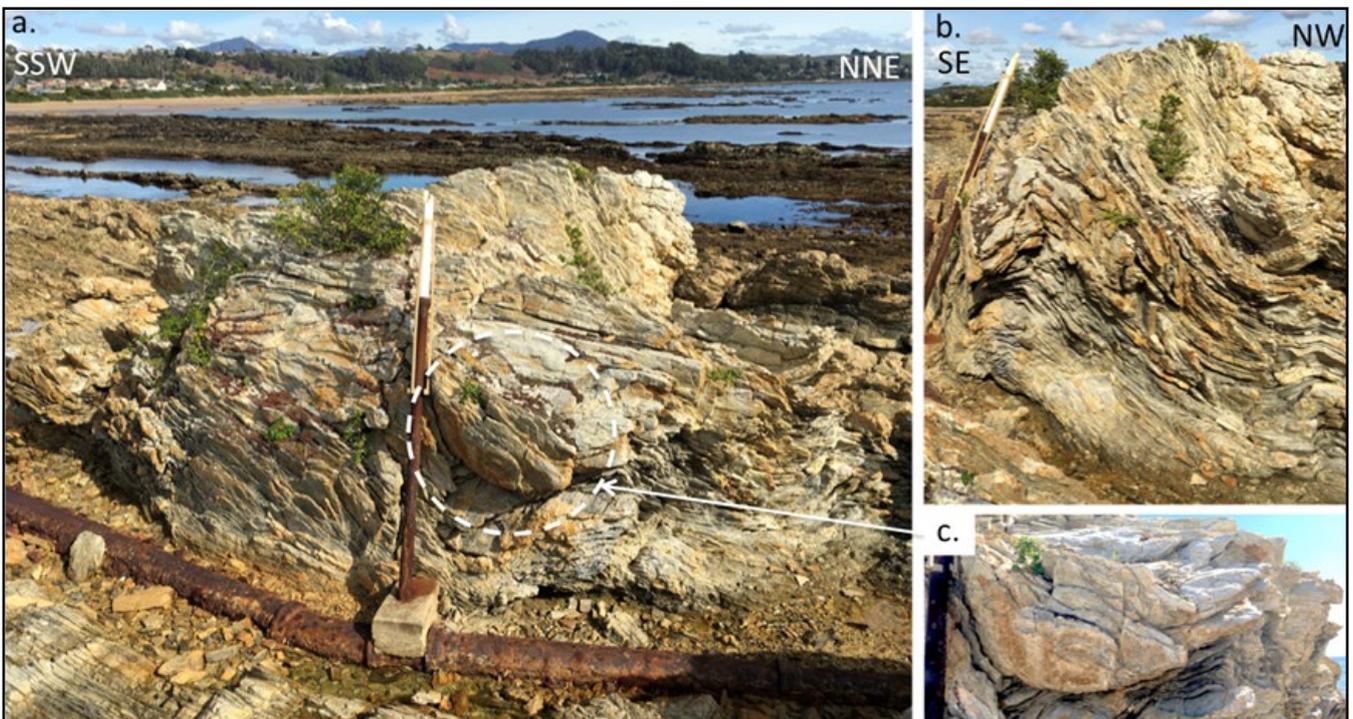


Figure 33. Views of quartzite stack near old sewer vent as part of Seagull Islet. a) View from the grassy knoll at Seagull Islet looking to the southwest with West Ulverstone beach in the background and sewer vent stack in the foreground. The curved hinge line of a refolded mesoscopic F2 is highlighted by the dashed circle. b) Profile view of refolded F2 folds in sewer vent stack (also see Figure 32). c) Curved hinge line of refolded east-closing isoclinal fold shown in the circled area in (a).

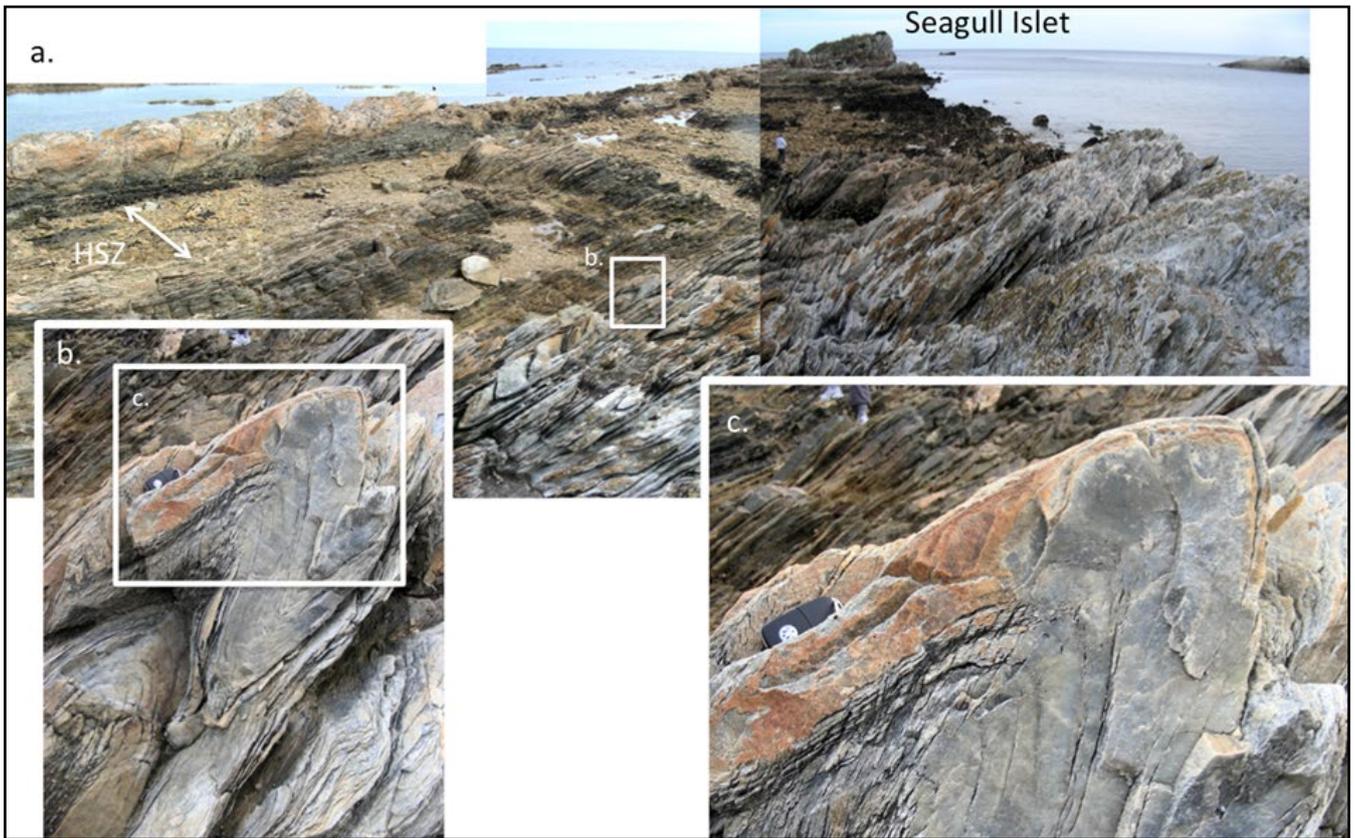


Figure 34. Chevron fold zone as asymmetric fold pairs with thin "bedded" quartzite along the eastern side of the Seagull Islet macro-shear lozenge. a) View looking north towards Seagull Islet showing the position of the chevron fold zone and the location of photograph (b). b) Down-plunge view of symmetric Z-vergent fold pair. c) Enlarged view of the antiformal hinge in (b) showing angular chevron form and the axial surface crenulation cleavage (ScC). Car key for scale.

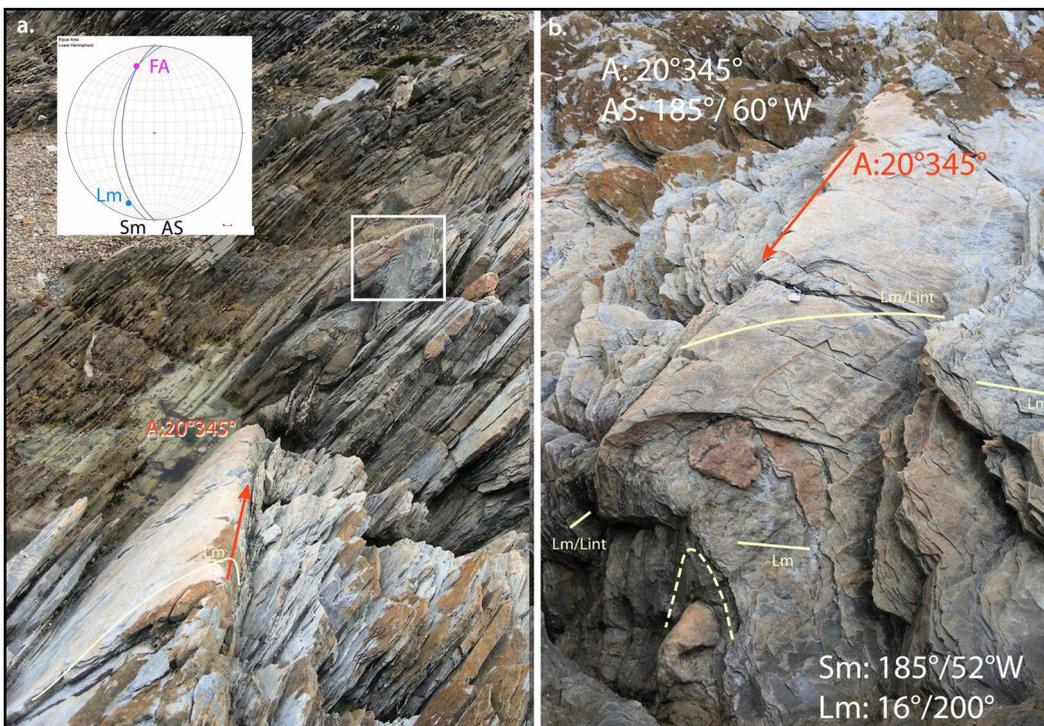


Figure 35. Plunging F2 asymmetric, Z-vergent folds in thin-bedded quartzite on the eastern (lower) limb of the F2 synformal macro-fold. a) Approximate down-plunge profile view of the asymmetric folds showing the lineation Lm (Lint) folded (pale yellow line trace) across the plunging fold hinge (red arrow). Inset stereonet shows the Fa and Lm relationships. b) View of the western limb of the plunging fold showing the folded lineation Lm.

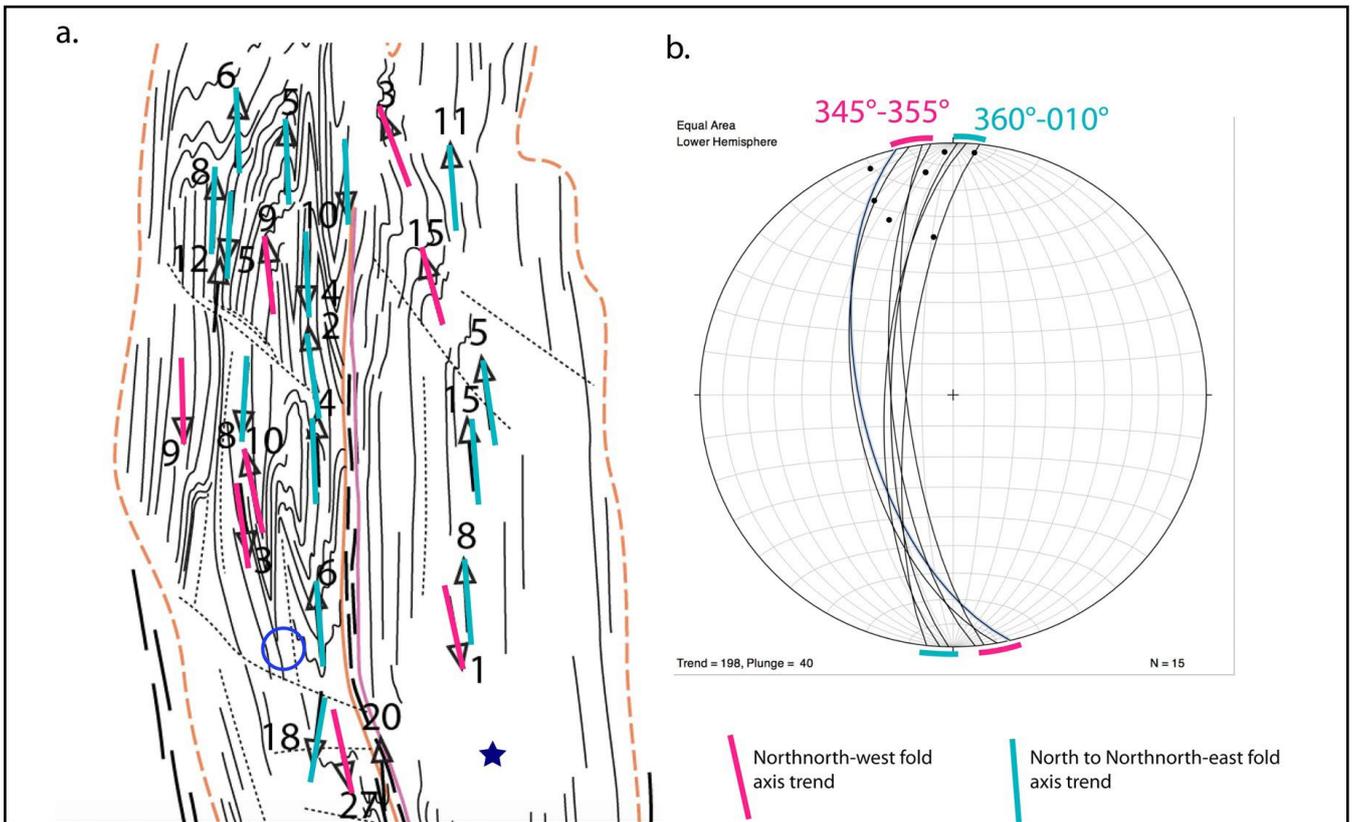


Figure 36. Enlarged map segment from Figure 22 showing the two obliquely intersecting fold sets at Seagull Islet within the quartzite shear-locale. a) Enlarged portion of the Seagull Islet form line map (Figure 18) showing the two fold sets (pink and blue line traces). The small blue circle shows the approximate location of the photograph in Figure 37 below. The black star represents the topographic knoll of the Islet. b) Stereonet of fold axial surface great circle traces and fold plunges (black dots). Note the two groupings of great circle traces that correspond to the fold sets highlighted in the form line map in (a).

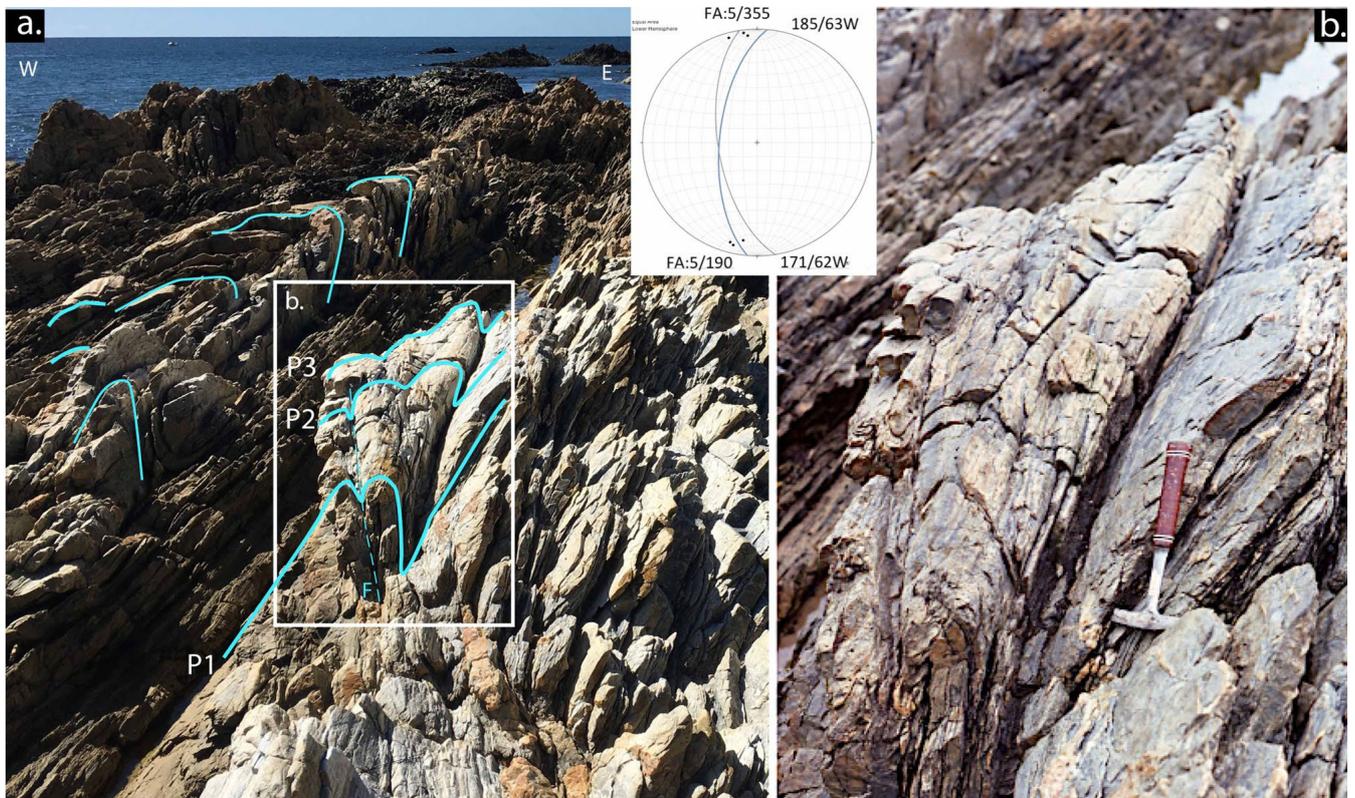


Figure 37. Compound asymmetric fold pair on the western limb of a sub-horizontal to north-plunging anticline (not shown off photo to the right). The compound form is due to the oblique intersection of a small 355° trending anticlinal fold with a -190° trending small anticlinal fold. The blue line traces provide serial sections through the fold pair. Note the asymmetric, Z-vergent form and the change in profile geometry (profiles P1, P2 to P3) northwards as the folds diverge. The folds have a common or shared hinge at their point of intersection (profile P1). This fold interference location is shown by the blue circle on the form line map in Figure 36. b) Overprinting upright fold hinges with two obliquely intersecting (-14°) upright fold "sets" north of the sewer vent. The stereonet (middle centre) shows the axial surface attitudes (great circle traces) and the fold axis measurements for the two main intersecting folds shown in (b).

Fold sets 3 and 4 locally interfere but both re-fold folds of set 2.

Stereonet of mesoscopic fold axes and their respective axial surfaces show the two distinct groupings for fold sets 3 and 4 (Figure 36b).

### 3.1.2.1 Significance of Folds within the Macro-shear Lozenge

The quartzite lozenges are internally deformed showing multiple mesoscopic fold sets that are part of the progressive evolution of the synformal F2 macro-fold, its progressive flattening and attenuation as a macro-shear lozenge within strongly to intensely deformed quartzite.

Different fold sets with different attitudes and trends occur within the macro-shear lozenge. These include:

1. recumbent isoclinal folds in the northern core of the shear lozenge (Figures 31, 32 and 33)
2. plunging Z-vergent F2 folds along the eastern (lower) fold limb (Figures 34 and 35)
3. synclinal keels in bounding shear zones (Figure 14), particularly along the eastern margin of the lozenge (Figures 44 and 45)

Refolded mesoscopic F2 folds in the core of the F2 synformal fold show variations in tightness. South of the sewer vent the F3 folds have gentle, open upright form (Figure 31) with ILA of 130° but have close form (ILA of 110°) on the northern face of the sewer vent fold stack (Figure 32).

Two obliquely intersecting F3 fold sets with varying separation angles occur through the middle to northern part of the lozenge. One set is approximately north-trending and the other more north-northwest-trending with separation angles of ~10°-30° (Figures 36 and 37).

The two sets of mutually interfering upright folds occupy distinct zones or domains with subtle fold interference along the length of the macro-shear lozenge (Figures 22b and 36). Upright, north-trending folds dominate the structure of the quartzite (stereonet, Figure 23). These folds have greater lateral continuity and appear to isolate or "surround" the north-northwest trending folds along the length of the quartzite lozenge (Figure 22).

Interference relationships between these fold sets are best observed north of the Sewer Vent, level with the Seagull Islet knoll/island (Figures 36 and 37). The fold sets have distinct axial surface strike trends of 345°-355° and 360°-010° (Figure 36b), as well as distinct NNW and NNE fold plunges (pink and blue arrows respectively, Figure 36b). Once again, the 360°-010° trending folds are dominant and have greater lateral continuity where they appear to isolate or "surround" the 345°-355° trending folds (Figures 36a, 37 and 38a).

Locally fold interference (location shown by the blue circle, Figure 36) is shown by the confluence of two fold hinges with a ~14° axial divergence (Figure 37). Serial

profiles P1, P2 and P3 (blue line traces Figure 37a) show the form of the interference with an apparent shared axial surface at their point of intersection (profile P1 blue line trace, Figure 37a). The folds adopt individual forms (profiles P2 and P3, Figure 37a) away from their intersection point. The NNW fold appears to have a straight or linear hinge line and the NNE fold hinge lines appear to curve into, or swing into sub-parallelism with, the NNW hinge line (Figure 37). The NNE fold also shows a plunge change from sub-horizontal to a gentle south plunge at the intersection (see black dots on the stereonet, Figure 36). The NNW hinge line also shows a subtle change from sub-horizontal at the fold intersection to a gentle north plunge way from the intersection point (see black dots on the stereonet, Figure 37).

### 3.1.2.2 Refolding Analysis and Significance of Two Fold Sets

Overprinting relationships are enigmatic. In summary, the N-S set appears dominant, showing 1) folds with greater amplitudes and more continuous hinge lines, and 2) isolating N-NW trending folds between larger dominant N-S fold hinge lines (Figure 36a). The N-NW folds appear to have restricted occurrence between the larger more continuous N-S fold hinge lines, particularly north of the sewer vent (Figures 37a and 38a).

The refolding relationships within a layer with preexisting folds are determined by the early fold fold scale (size of fold hinges) and the early fold tightness relative to the scale and amplitude of the second phase overprinting folds (see Ghosh, 1993, p.340-351). At Seagull Islet the second-generation folds (F3b) have larger amplitudes, and therefore dominate and override the F3a folds. As a consequence, they also appear to isolate the F3a fold hinges (Figures 37 and 38).

### Interpretation

The NW (345°-355°) trending set, interpreted as F3a folding, is coaxial with the initial recumbent tight to isoclinal F2 macro-fold in the quartzite (compare with stereonet DG89-169, Figure 25 for the main hinge). The limb-related, Z-vergent asymmetric fold pairs are considered mesoscopic vergence folds on the lower limb of the F2 macroscopic synform (Figures 34 and 35).

The N-S (360°-010°) folds re-fold the core and western overturned limb of the F2 macrofold and have been designated F3b. Previously these upright N-S folds were related to the younger Devonian folding responsible for the regional Forth Anticline. However, these folds are not present within the high strain zones that envelope the Seagull Islet Macro-shear lozenge but are restricted to the core of the quartzite lozenge. This suggests that they are part of the deformation continuum with development, isolation and refolding of the core synformal macro-fold during progressive north-over-south shear emplacement.

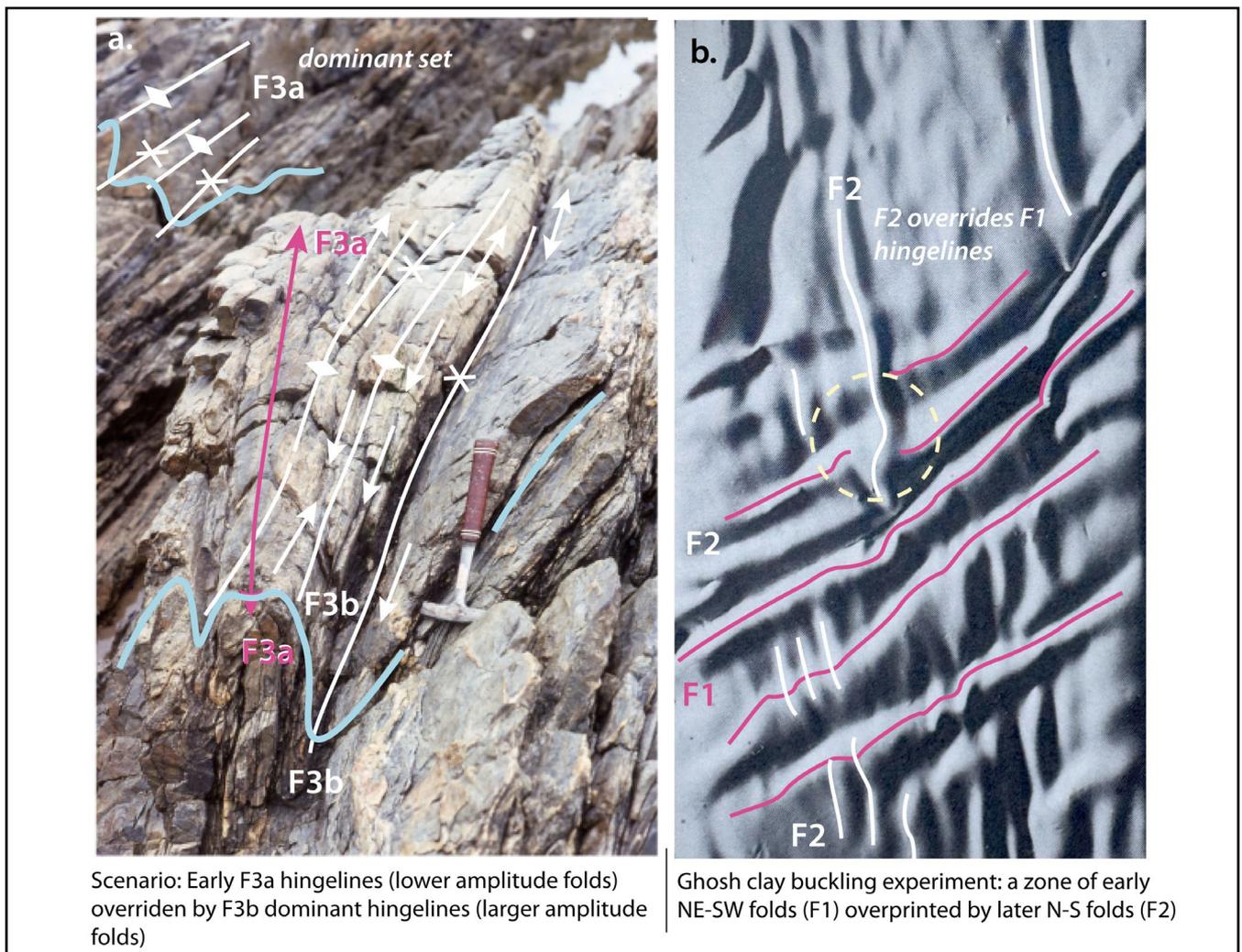


Figure 38. Overprinting and refolding relationships of obliquely intersecting fold sets. a) Seagull Islet example north of the Sewer vent. The interpreted early upright F3 fold (designated F3a) is shown by the pink line trace with the arrowheads indicating the fold plunge directions. The axial surface traces of the inferred superimposed F3b folds are shown by the white line traces with arrows indicating the plunge direction of hinge line segments. b) Superimposed folding in single layer sheet (fig. 15.14a from Ghosh, 1993).

### 3.1.2.3 Shear Zone Margins of the Seagull Islet Macro-shear Lozenge

Margins of the quartzite macro-lozenge are shear zones of both mylonitic, platy quartzite (Figures 39, 40 and 41) interdigitating with quartz-mica phyllite (Figures 42 and 43). These bound and infiltrate the margins of the quartzite lozenge resulting in segmentation and eventual isolation of quartzite pods, a form of shear zone cannibalisation of the larger quartzite bodies (Figures 20 and 40). The zones are dominated by tadpole-like remnants of synformal closures in quartzite at the current structural level (Figures 44 and 45).

The marginal high strain zones are a mix of intercalated platy quartzite mylonite (Figure 39) tectonically interdigitating with intensely transposed pelitic layering (Figure 43b). The platy quartzite contains isoclinally folded and strung out quartz veins within the intense  $S_m$  (Figure 41).

### 3.1.2.4 Macro Geometry of the Seagull Islet Shear Lozenge

The core of the Seagull Islet Shear Lozenge is an F2 nappe-like synform within quartzite. It has reclined geometry and is bounded and cut by high strain zones of platy quartzite,

quartz-mica schist and phyllite (Figure 46). The profile is based on the serial profiles shown in Figure 26 as well as the detailed observations made through the Seagull Islet quartzite pod (e.g. Figures 27 and 28).

### 3.1.3 Picnic Point Shear Lozenge

The Picnic Point shear lozenge is a smaller (~115 m length and ~12-14 m width scale), elongated quartzite body due south of the Seagull Islet shear lozenge (left sketch map, Figure 47). It has oppositely curved, tapered north and south terminations (Figure 47). Like the Seagull Islet lozenge it is cored by a tight to isoclinal, synformal fold (Figure 48). Made up of thin and thicker bedded quartzite the lozenge shows varying internal structure (Figure 47) including dismembered isoclinal folds at the southern termination (Figures 49 and 50), internal boudin structure (Figure 51), both northeast-trending sinistral and northwest-trending dextral shear bands (Figure 47) and dome and basin fold interference (Figure 47). The large scale, northeast-trending sinistral and northwest-trending dextral shear bands (Figure 47b) give an MP2 vector of  $182^\circ$  (magnetic).

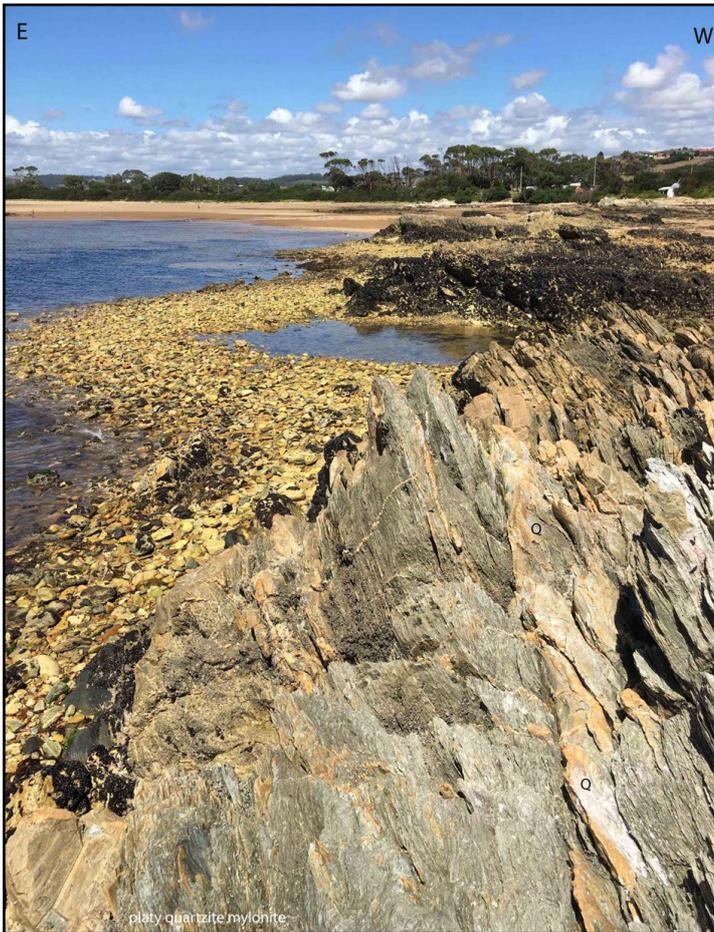


Figure 39. (Left). Mylonitic platy quartzite along the eastern margin of the Seagull Islet macro-lozenge showing a tightly and obliquely infolded, pale orange quartzite layer giving an apparent fault truncation (photo right). Note the platy quartzite Sm occurs on both sides of the infolded layer and transects the layer (photo bottom right).

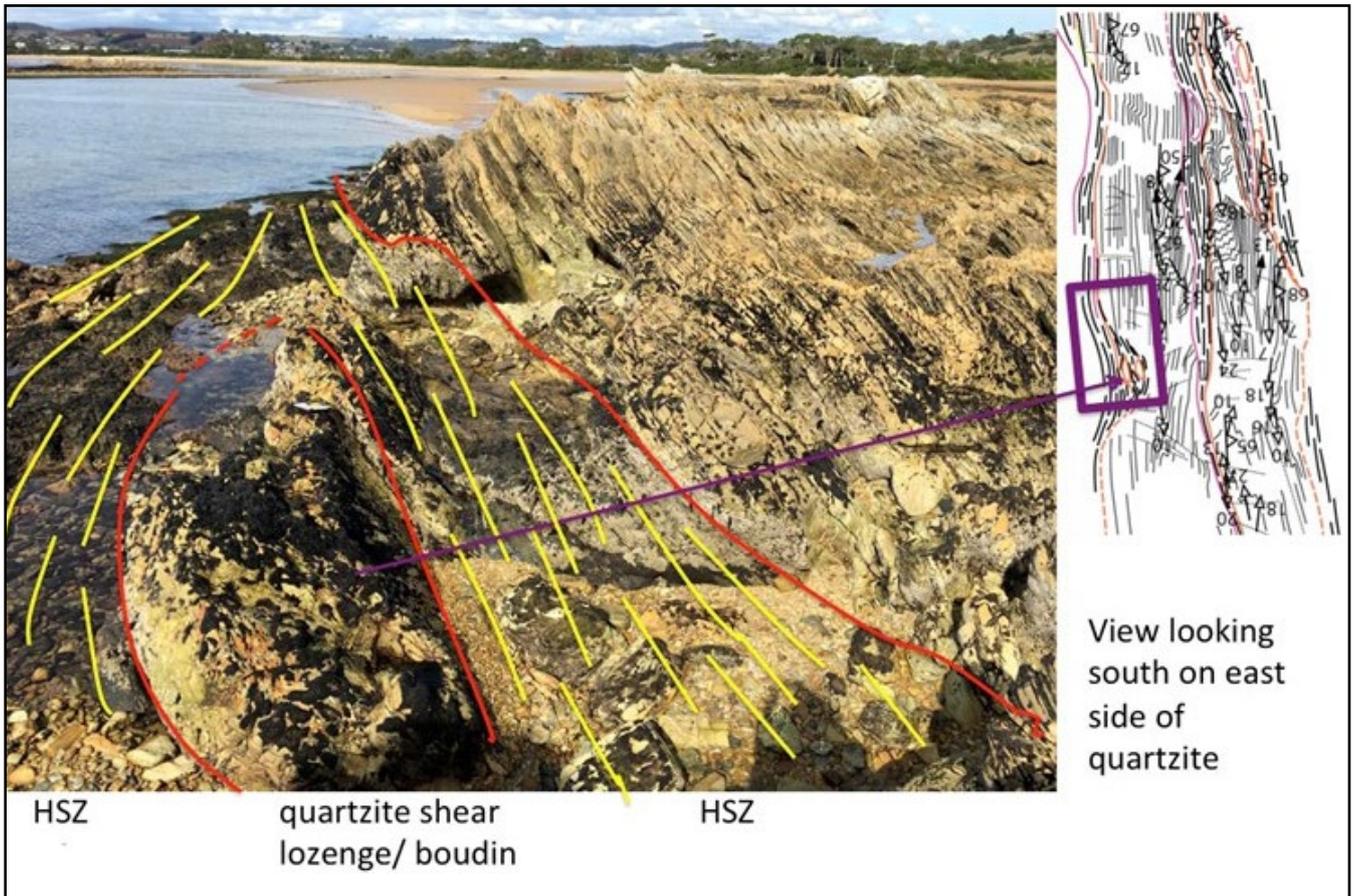


Figure 40. Segmentation and isolation of quartzite pod within the eastern bounding (basal) shear zone for the Seagull Islet macro-lozenge. Platy quartzite mylonitisation within the upper and lower bounding shear zones results in cannibalisation of the main quartzite body through segmentation and isolation as pods within the high strain zones.

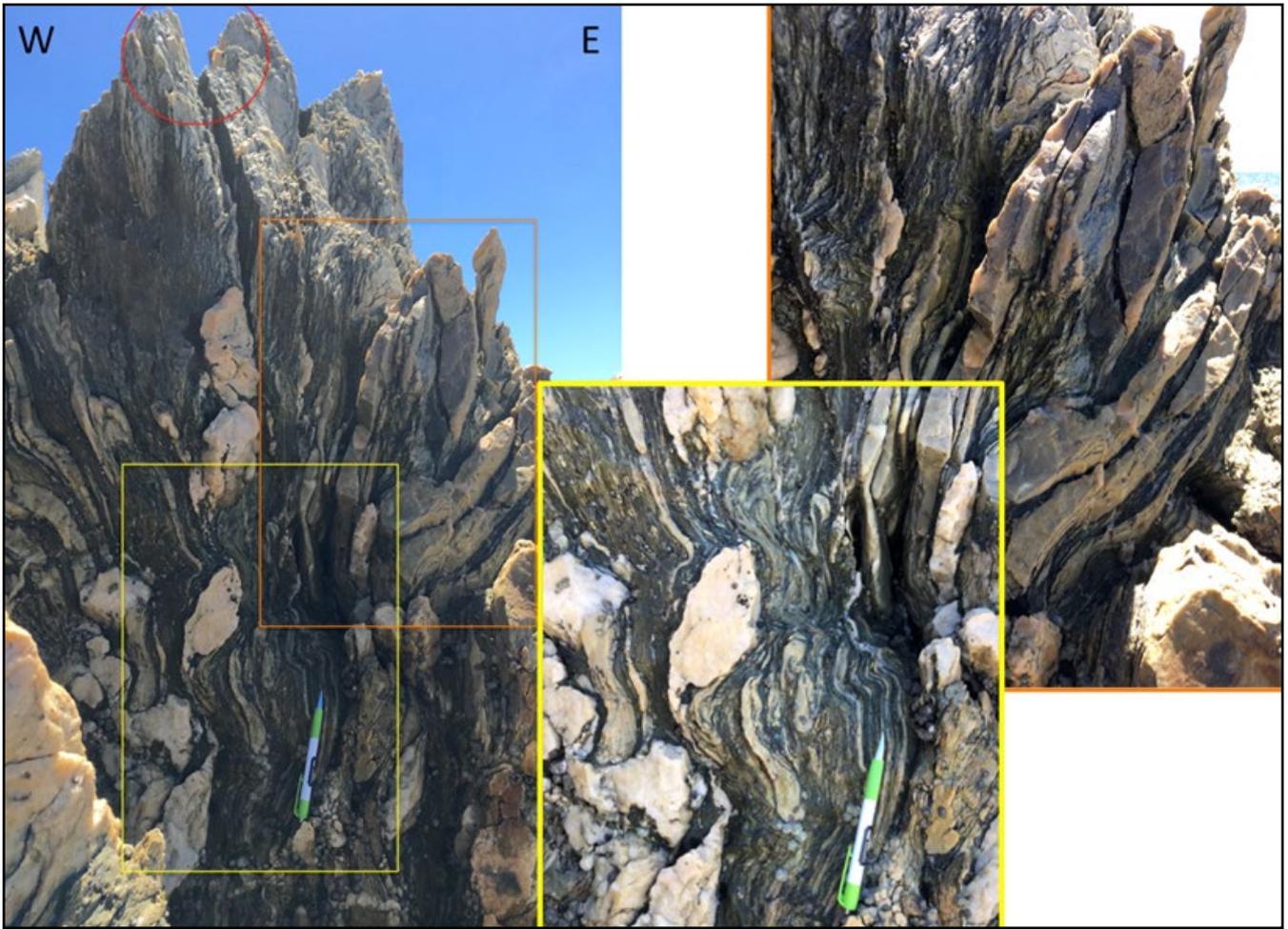


Figure 41. Platy quartzite along the eastern margin of the Seagull Islet macro-shear lozenge. The quartzite has a thin banded, platy-like character enclosing flattened and attenuated isoclinal folds in thicker quartzite layers (upper right) and dismembered tad pole-like fragments in formerly isoclinally folded quartz veins (white). This sits inboard to the thin-banded transposed pelite along the western margin of the synformal keel in Figure 44. Compare the position of the red circles in both figures that act as common points in the photographs.

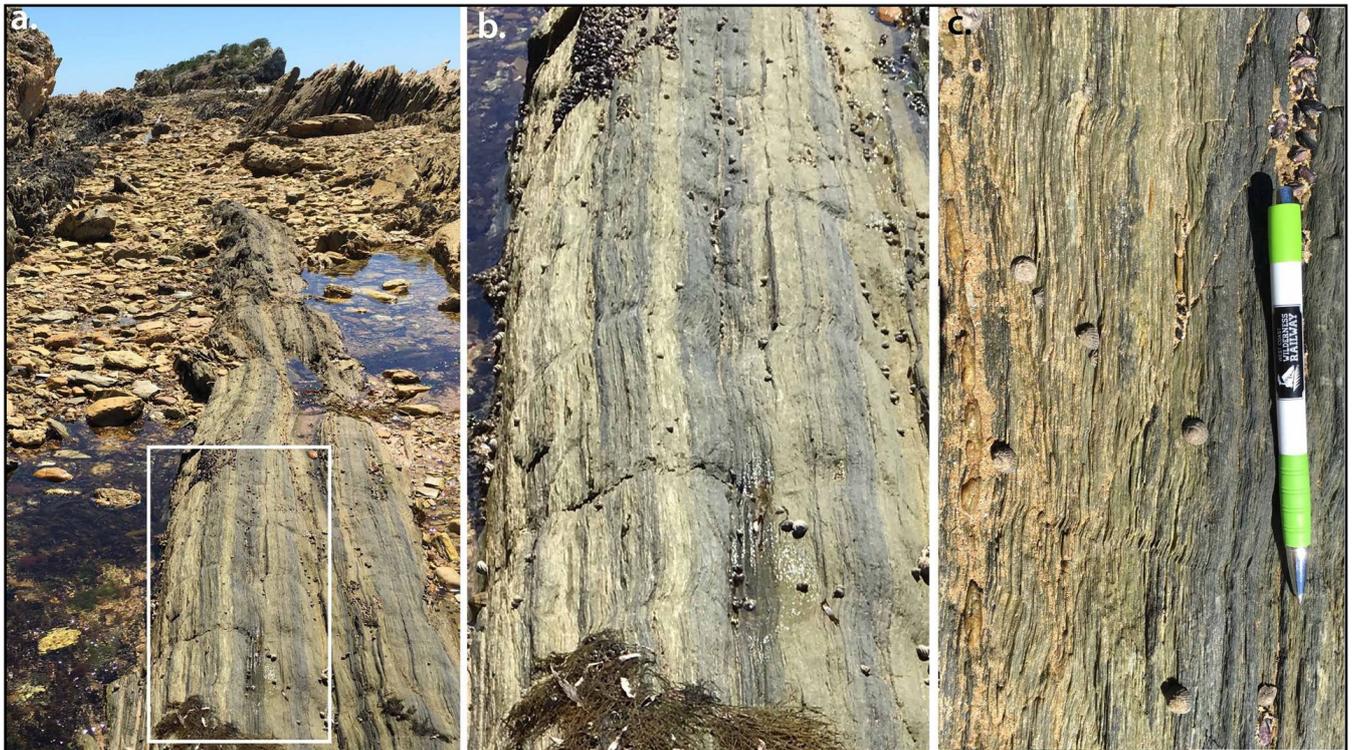


Figure 42. High strain zone fabrics in central shear zone, Seagull Islet platform. a) Eroded corridor of high strain fabrics delineating the shear zone. b) The zone consists of strong to intense foliation  $S_m$  in transposition layering, caused by interdigitation of platy quartzite (buff colour layer on photo left), quartz-mica phyllite olive green coloured layers) and black phyllite (dark grey layers). c) Close up of the transposition foliation  $S_m$  within the shear zone.

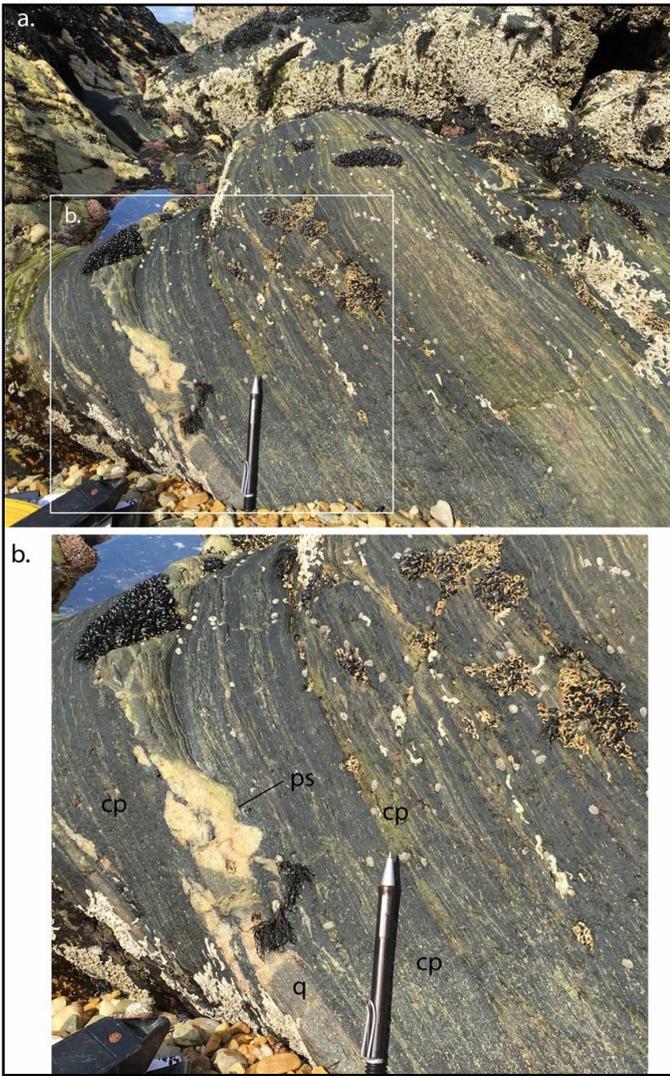


Figure 43 (Left). Fabric of the eastern marginal HSZ to the Seagull Islet macro-shear lozenge just south of Seagull Islet knoll. a) Transposed layering within intensely foliated and structurally intercalated dark grey phyllite, green chloritic phyllite and thin quartzite layers (q). b) Enlargement of part of (a). cp: chloritic phyllite. q: quartzite. ps: pressure solution along vein contact.

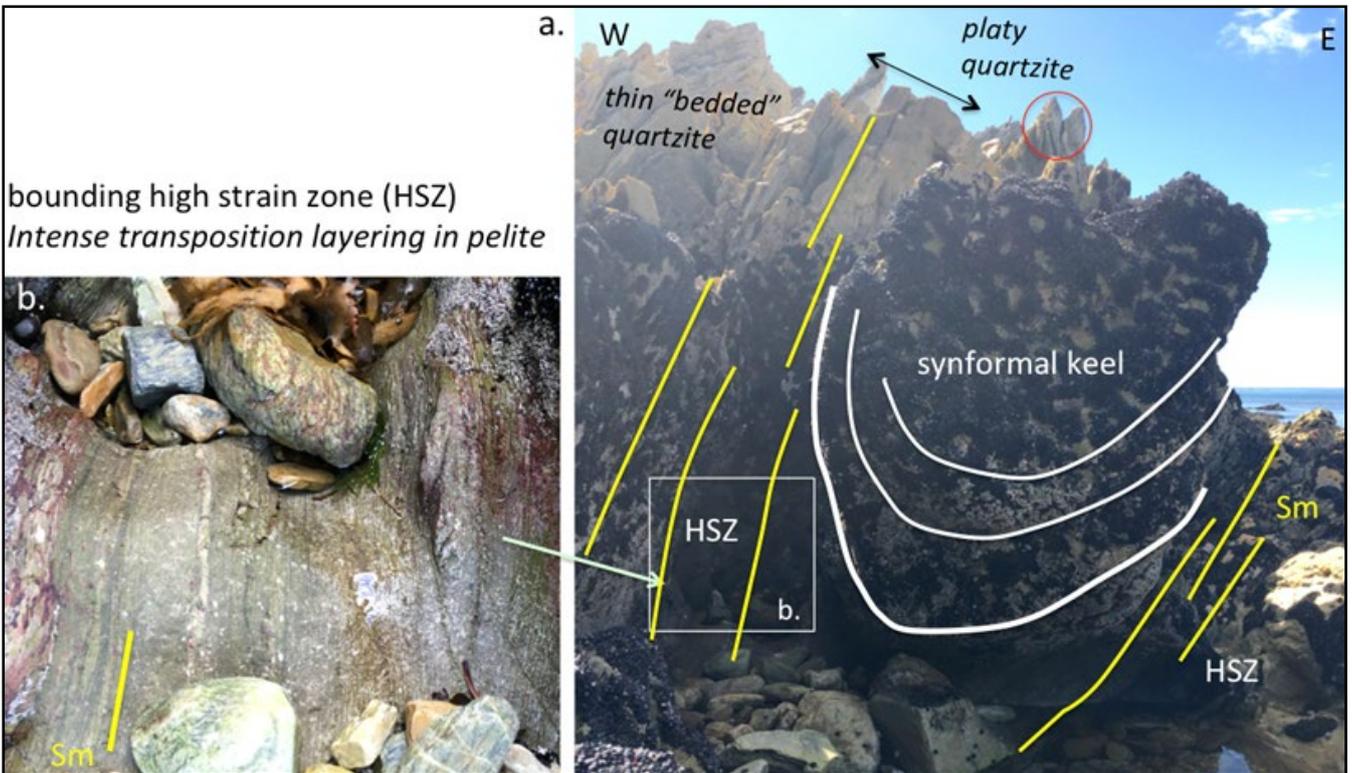


Figure 44. Eastern margin HSZ to the Seagull Islet macro-scale shear lozenge. a) Synformal keel preserved in quartzite lozenge within the high strain zone. b) Structurally intercalated quartz-mica schist/phyllite and thin quartzite bands within the high strain zone enveloping the synform.

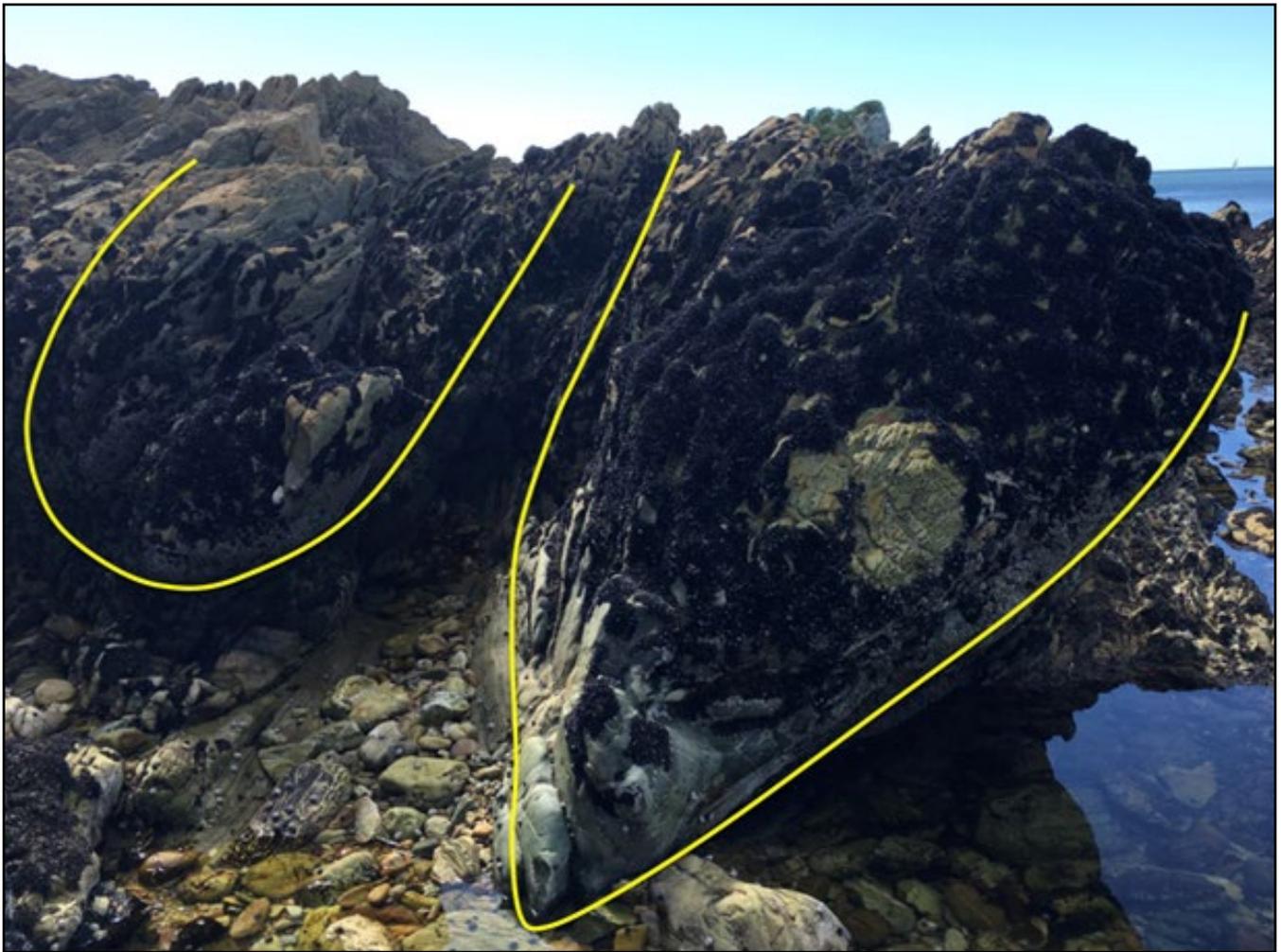


Figure 45. Double synformal keels preserved in quartzite lozenge within the high strain zone bounding the eastern margin of the Seagull Islet macro-shear lozenge.

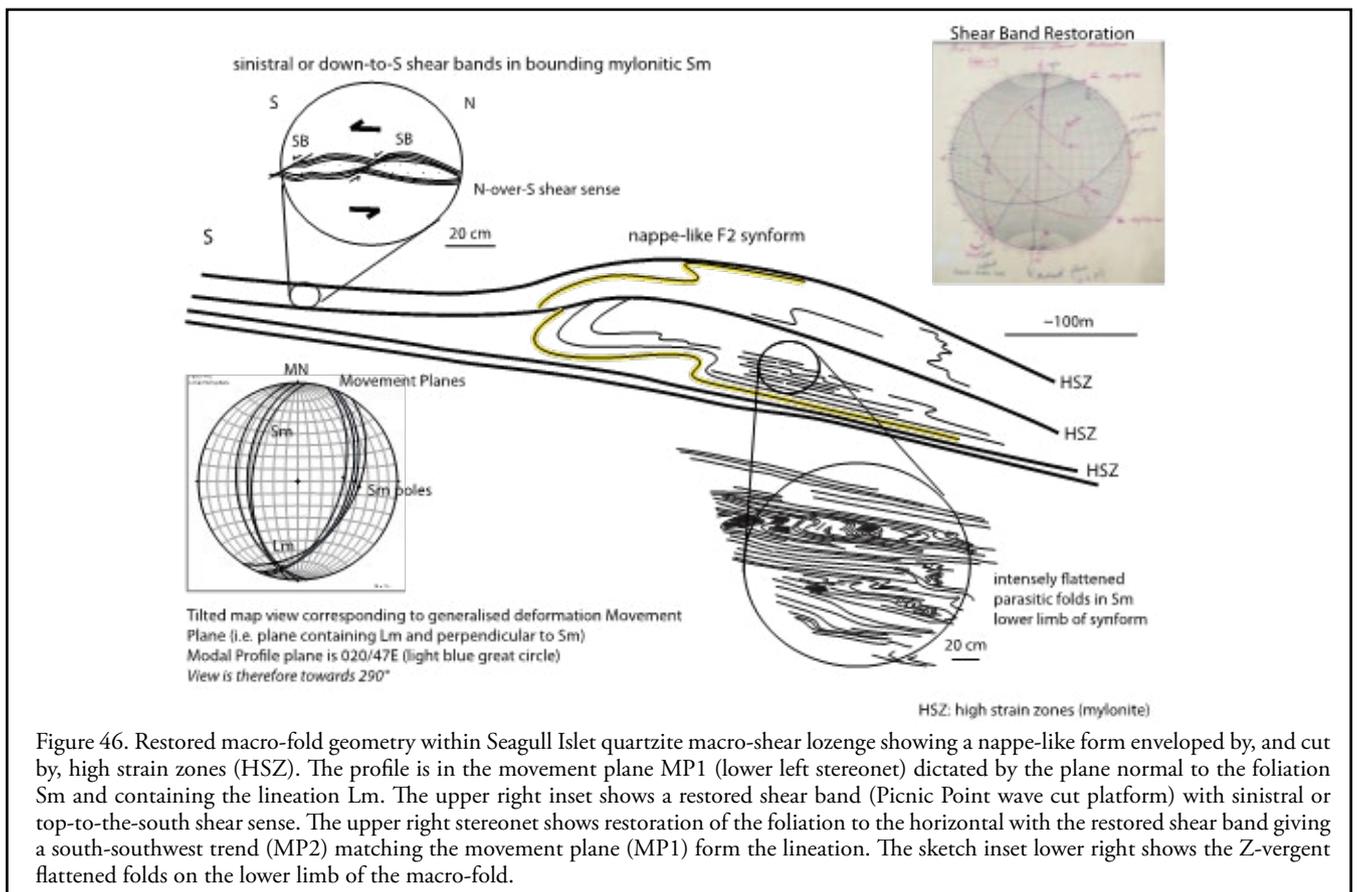


Figure 46. Restored macro-fold geometry within Seagull Islet quartzite macro-shear lozenge showing a nappe-like form enveloped by, and cut by, high strain zones (HSZ). The profile is in the movement plane MP1 (lower left stereonet) dictated by the plane normal to the foliation Sm and containing the lineation Lm. The upper right inset shows a restored shear band (Picnic Point wave cut platform) with sinistral or top-to-the-south shear sense. The upper right stereonet shows restoration of the foliation to the horizontal with the restored shear band giving a south-southwest trend (MP2) matching the movement plane (MP1) from the lineation. The sketch inset lower right shows the Z-vergent flattened folds on the lower limb of the macro-fold.

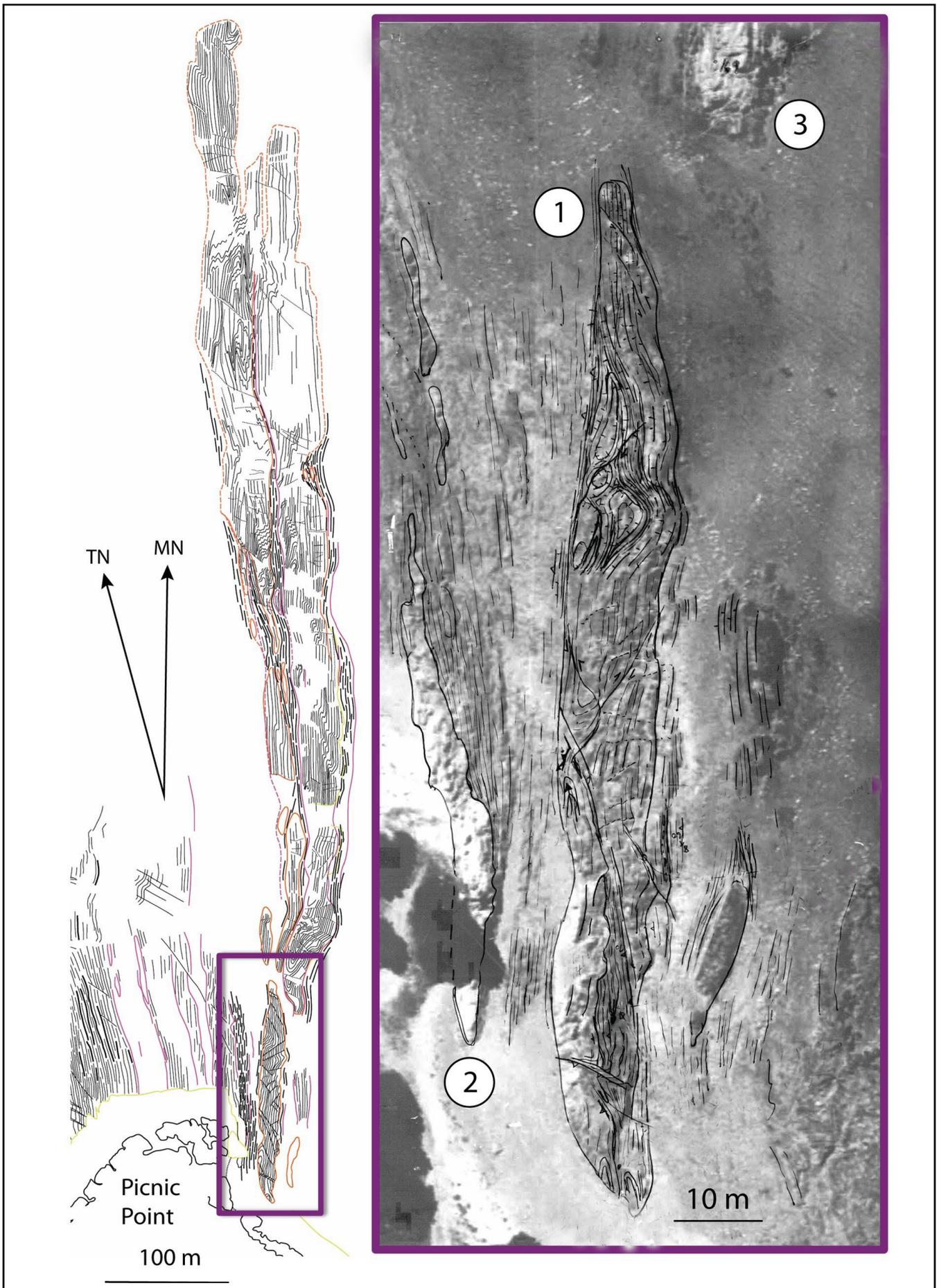


Figure 47. Form line maps of the quartzite shear lozenges from Picnic Point extending to Seagull Islet. a) Location map of Picnic Point shear lozenge on form line map base. The purple rectangle shows the position of the lozenge. b) Structural form line map of the Picnic Point shear lozenge on enlarged air photo base. Circled 1: Picnic Point lozenge. Circled 2: smaller quartzite lozenge flanking the northeast corner of Picnic Point. Circled 3: southern termination of Seagull Islet lozenge.



Figure 48. Picnic Point shear lozenge profile. a) View looking south at the west end of Picnic Point Beach. The yellow rectangle is the area enlarged in (b). Form lines in So/Sm are shown by the white line traces. b) Photo profile of the north end of the Picnic Point shear lozenge shown in map view in Figure 47 with profile positioned near the circled number 1. The lozenge contains a tight to isoclinal synformal fold closure in bedded flaggy quartzite with a fanning axial surface foliation (Sm) shown by the fine white line traces.

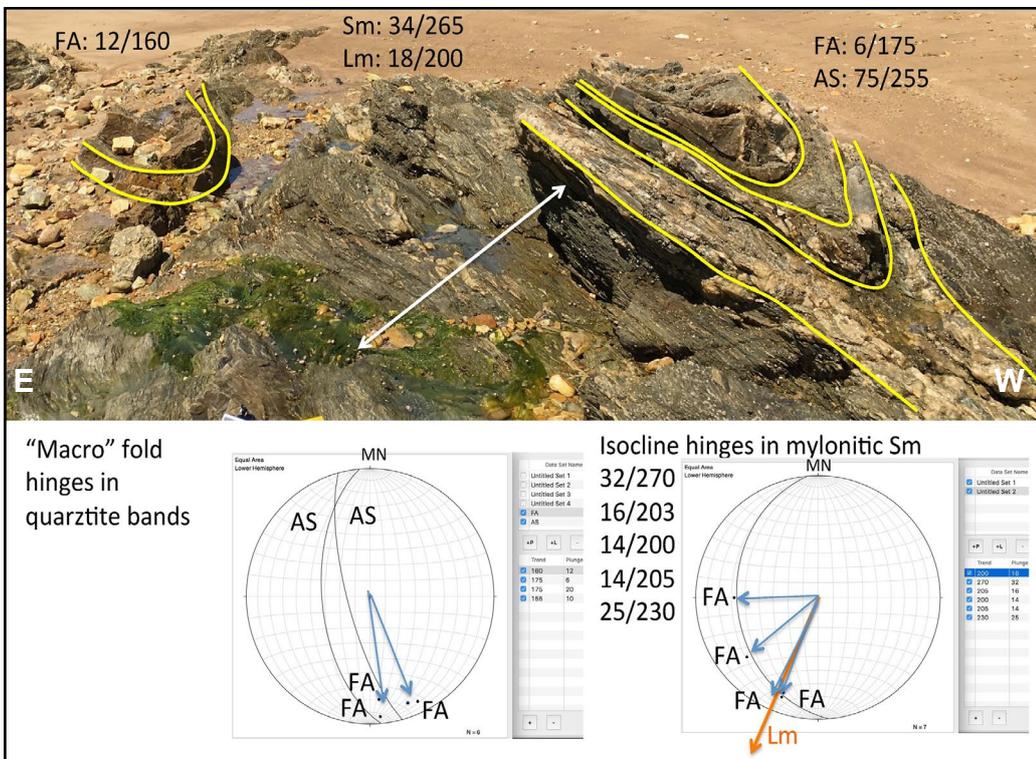


Figure 49. Dismembered isoclinal fold hinges in quartzite enclosed by platy quartz mylonite at the southern termination of the Picnic Point shear lozenge. All structural data are magnetic.

Left stereonet: Axial surface great circles and fold axes of the two quartzite fold hinges. The blue arrows show the fold plunge trends.

Right stereonet: Sm great circle trace with lineation Lm (orange line trend) and fold hinge plunges (FA) of small-scale rootless folds within the Sm (plunge trends shown by the blue line traces).

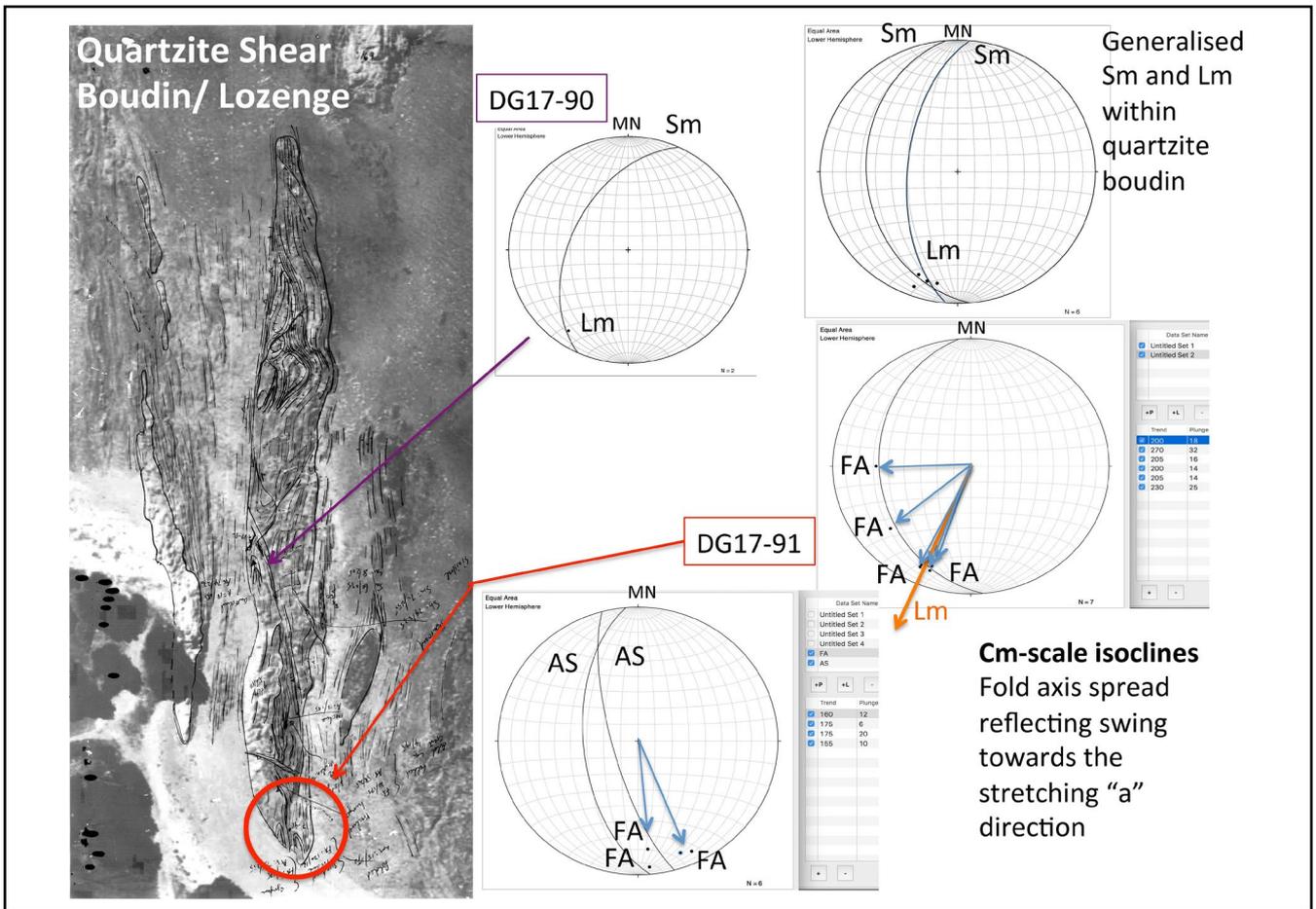


Figure 50. Structural relationships between fold axes (FA), fold axial surfaces (AS), the dominant foliation (Sm) and the contained mineral lination (Lm) in two parts of the Picnic Point Shear lozenge (stations DG17-9 and DG17-91). The lination within Sm and the fold axes are all south-plunging in the southern half of the shear lozenge. At the southern tail of the pod cm-scale isoclines show a swing towards the stretching lination Lm. These lie within the mylonitic foliation that truncates folds within thicker bedded quartzite (see Figure 49).

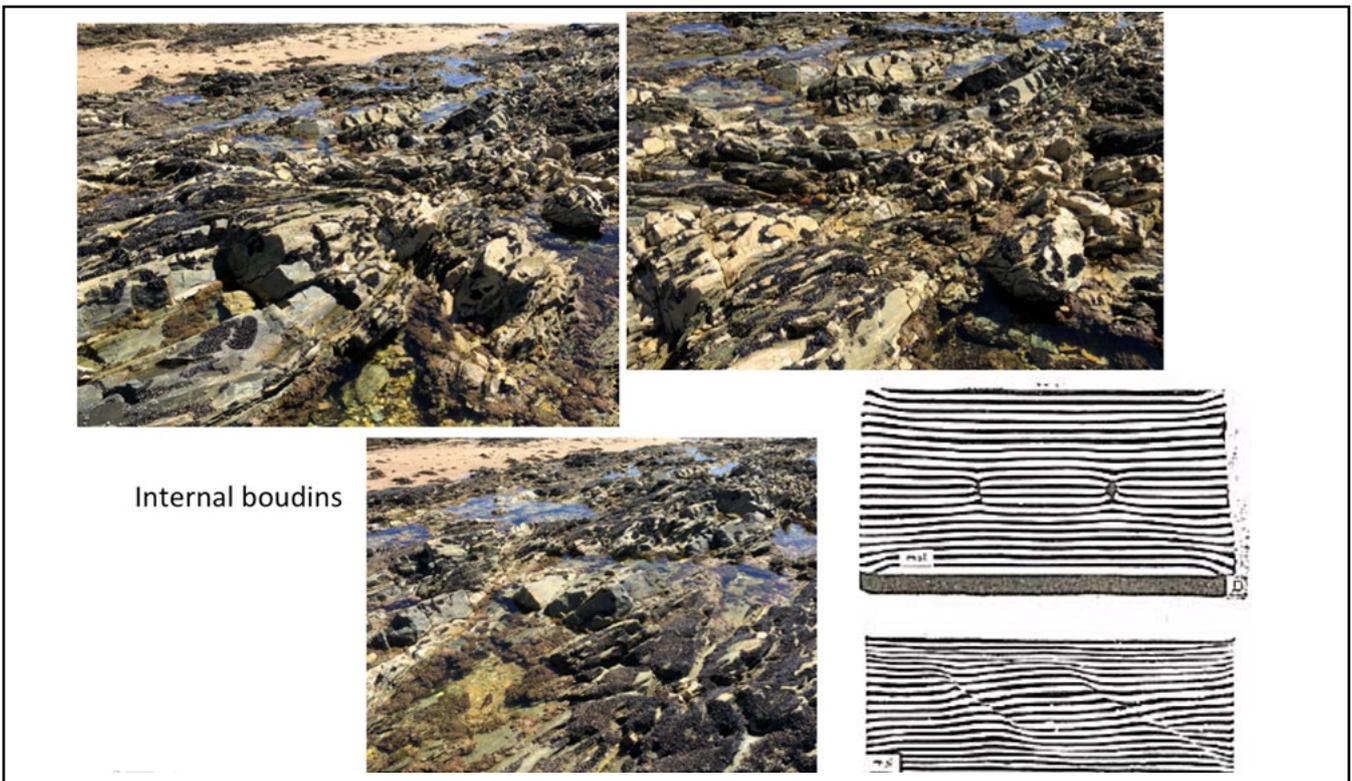


Figure 51. Internal boudins with quartz gash veins occur in the middle of the Picnic Point Shear lozenge. These are highlighted by a pinching-type convergence terminating in voids (gash veins). Compare with the uppermost multilayer model (diagram bottom right). The bottom multilayer model shows asymmetric shear bands that also occur on the outcrop (Figure 47). The model clay-multilayer experiments are from Ghosh (1993, fig. 17.36).

The rounded, attenuated, southern termination of the lozenge consists of two mesoscopic, westerly inclined, gently south plunging, rootless, synformal fold cores in a thicker quartzite band. Both hinges are enveloped by mylonitic, quartz-mica schist and schistose quartzite (Figure 49). The schistose rocks contain centimetre-scale, rootless isoclinal folds within the foliation Sm. These isoclinal folds show a 70° fold axis spread with plunges towards west

and the southwest (Figures 49 and 50). South of the southern termination of the lozenge plunging isoclinal folds in quartzite are considered part of this segmented Seagull Islet-Picnic Point lozenge quartzite body (Figure 52). The Picnic Point lozenge is enveloped by mylonitic, quartz-mica schist and schistose quartzite in both the hanging wall (Figure 15) and the footwall to the pod (Figure 53).



Figure 52 (Left). Plunging F2 isoclinal folds in quartzite layer exposed on the Picnic Point beach just east of Picnic Point. This is most likely another segmented part of Picnic Point shear boudin or macro-lozenge.



Figure 53. Platy quartzite mylonite exposed on the beach as part of the footwall to the Picnic Point Shear lozenge. Note the top-to-the-south shear bands (centre mid photo) and the strung out form of thin quartzite layers.

### 3.1.4 Quartzite Islands East of Seagull Islet

Segmented, discontinuous quartzite layers east of Seagull Islet Quartzite Shear Lozenge form a series of islands at high tide (Figure 54). The apparent lozenges have length dimensions of ~100 m and widths of ~20-30 m. The segmentation has a matching form of tapered, tear-drop shear band geometry (Figure 55a, b) controlled by ~30-50 m spaced, large scale sinistral and dextral shear band-like structures (Figure 55b). Quartzite within the lozenges has an overall 50°-60° west dip (Figure 55c),

with structural profiles across the individual lozenges (pink lines A, B, C, D and E, Figure 55c) showing dominant S-vergent (top-to-the-south) asymmetric fold pairs (Figure 55d). Some of these folds, particularly in the southernmost "island" have markedly curved hinge lines (Figure 56) typical of sheath folds formed in a general/simple shear.

The train of shear lozenges are segmented and bounded by platy quartz mylonite seen in places along margins of the pods (Figure 57).



Figure 54. Location of the quartzite island chain east of Seagull Islet. Google satellite image as base. More detailed imagery is shown in Figure 55.

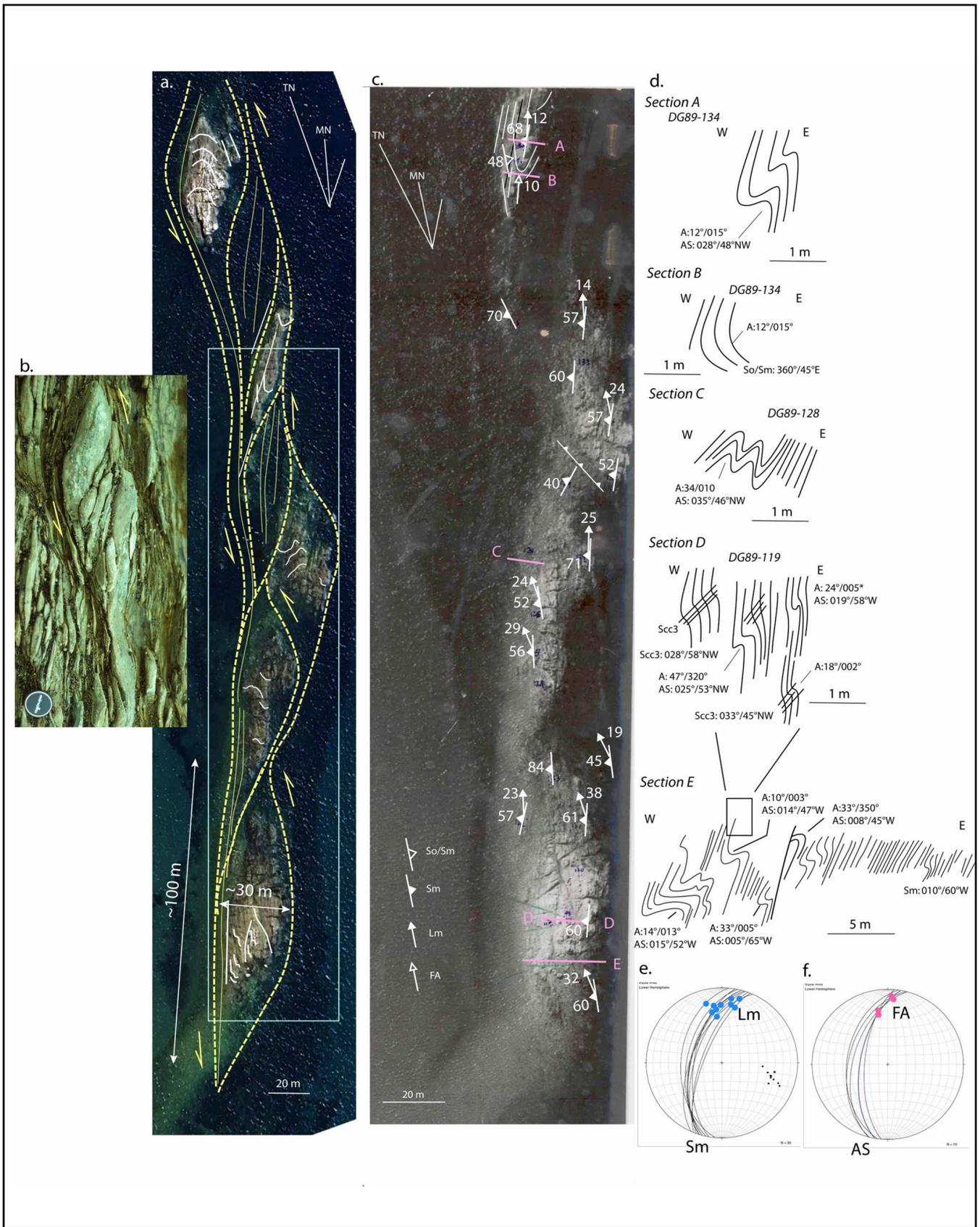


Figure 55. Structure of the quartzite island chain east of Seagull Islet shown in maps, profiles and stereonet. a) Interpreted shear zone-lozenge pattern on Google satellite image base to cause apparent segmentation of the quartzite into separate lozenges. b) Small scale example of shear lozenges in quartzite at Picnic Point. Note the similarity in geometry with the macro-pattern in (a). b) Structural data of Sm, Lm and fold axis (FA) attitudes plotted on an air photo base. c) Profile sketches A through E across parts of the quartzite islands. Section line position are shown by the pink line traces in (b). e) Stereonet of total Sm (great circle traces) and Lm (blue dots) data. f) Fold data for the east island chain with Axial surface great circle traces and fold axes (FA) as red dots.

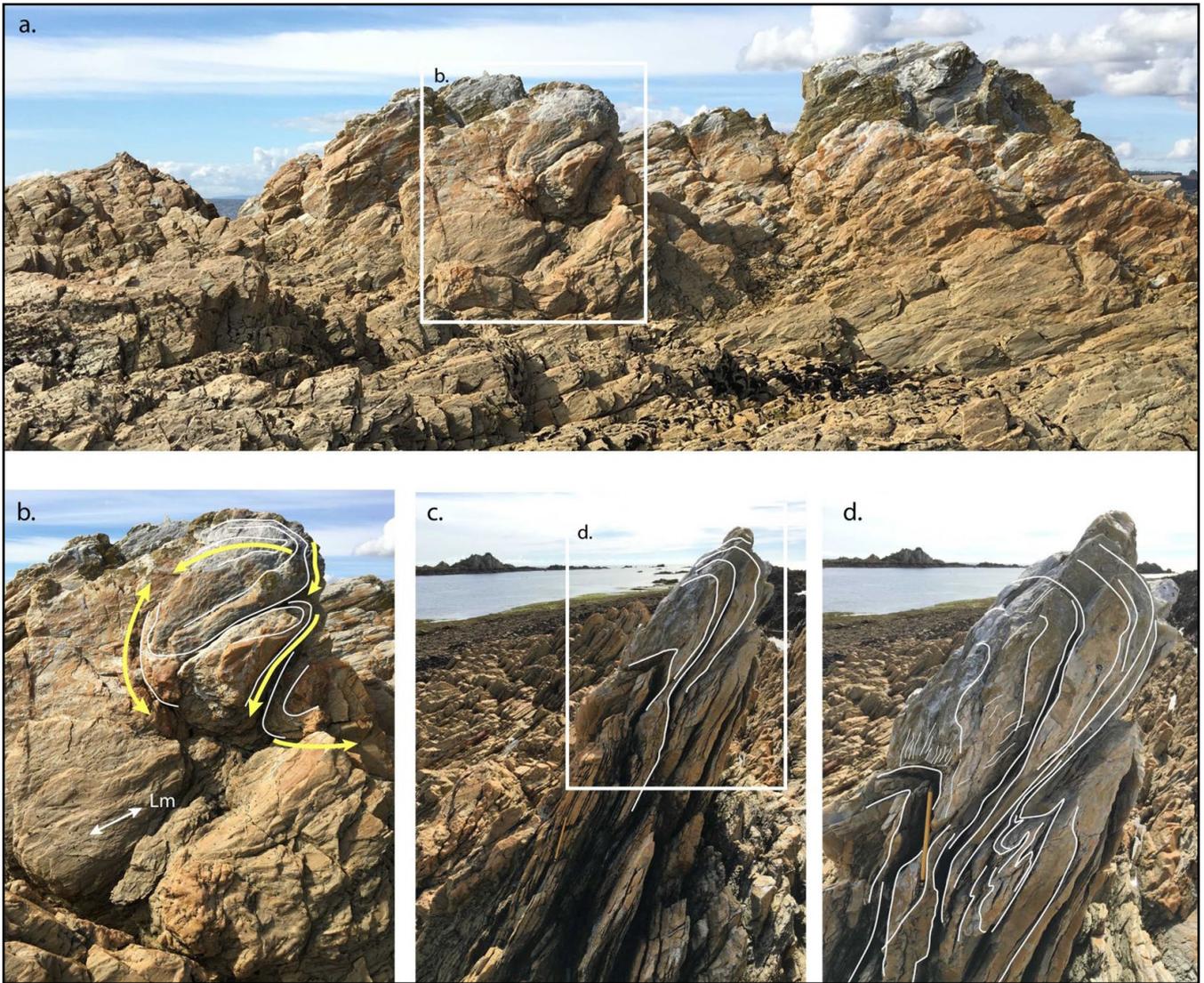


Figure 56. Plunging sheath-like folds within the first island of the east Island chain. a) Longitudinal view of island at low tide (view is to the east) showing north-plunging fold forms. b) is an enlargement of the area in (a) shown by the white rectangle. Yellow line traces highlight the markedly curved hinge lines. c) Approximate profile view of the fold shown in (b). d) is an enlargement of area highlighted in (c).



Figure 57 (Left). Outcrop relict of the bounding platy quartz mylonite that bounds the "islands" of flaggy quartzite. The "island" flanks and intervening low areas are mostly covered by sand and eroded quartzite fragments as slabs and cobbles. b) Enlargement of the platy quartzite mylonite shown by the rectangle in (a).

### 3.1.5 East Ulverstone Wavecut Platform

The East Ulverstone wave cut platform outcrops are the easternmost part, and therefore the structurally lowest part, of the west-dipping Ulverstone Metamorphic Sheet (Figure 9). The outcrop shows a transition from foliated zones with internally folded quartzite pods on the west (Figures 58, 59, 60 and 61), into intensely foliated, platy quartzite, quartz-mica schist and mica-quartz schist on the east (Figures 59, 62 and 63). The fabric transition across the East Ulverstone platform reflects the increase in strain towards the base of the Ulverstone Sheet and the contact with the underlying Forth H-G Metamorphic Sheet. The

projected interface between the Ulverstone Sheet and the Forth Metamorphic Sheet, designated as the East Ulverstone HSZ (Gray and Vicary, 2026), intercepts the beach just east of the East Ulverstone beach wave-cut platform.

Although the East Ulverstone platform does not have the marked augen or pod form shown at Seagull Islet and Picnic Point the quartzite bodies on the western part of this platform are enveloped by schistose platy quartzite (Figures 60 and 61c). They also show homoclinal west-dip and contain asymmetric S-vergent fold pairs (Figures 60 and 61) that are reminiscent of the islands east of Seagull Islet (compare with profiles in Figure 55d).

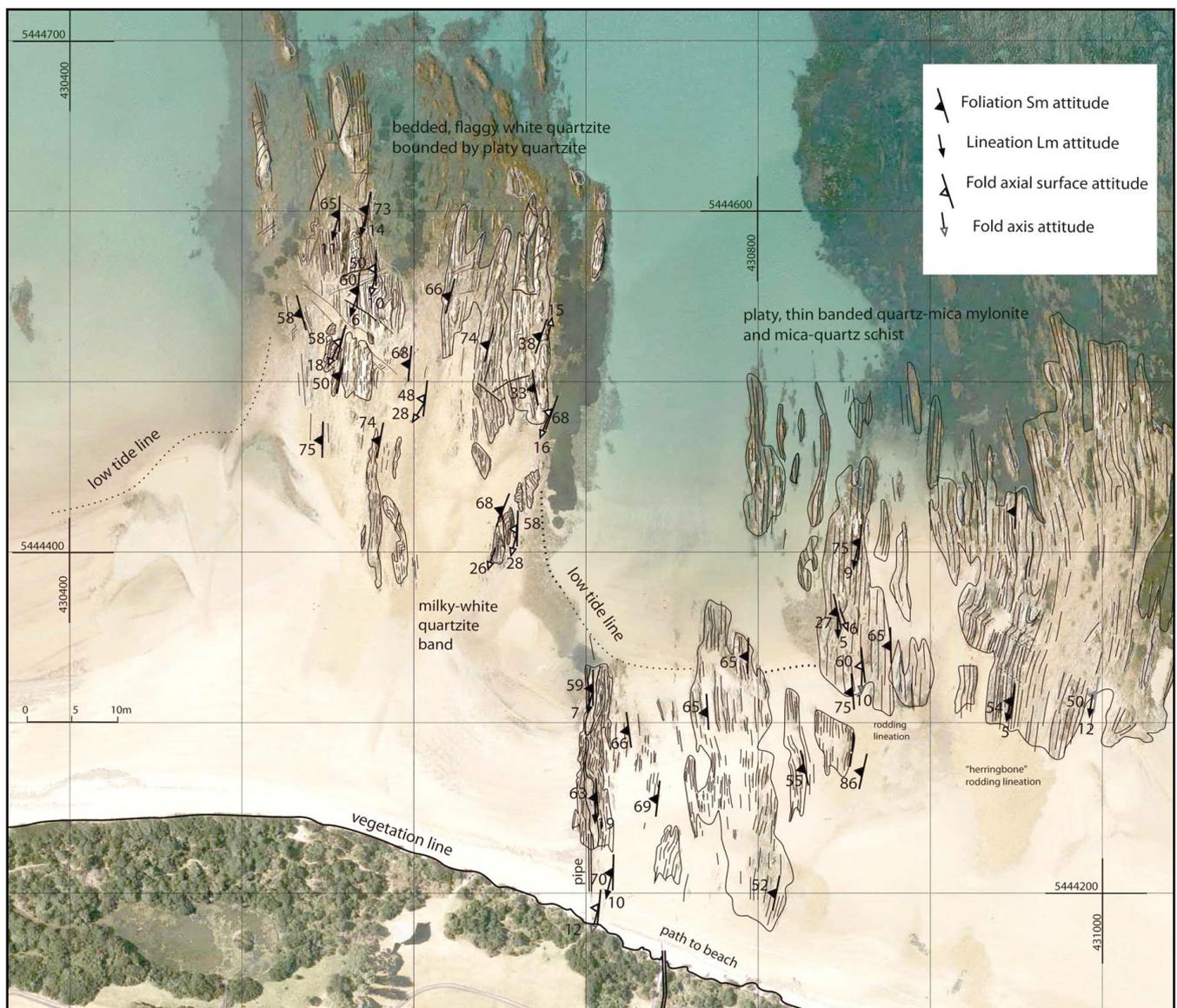
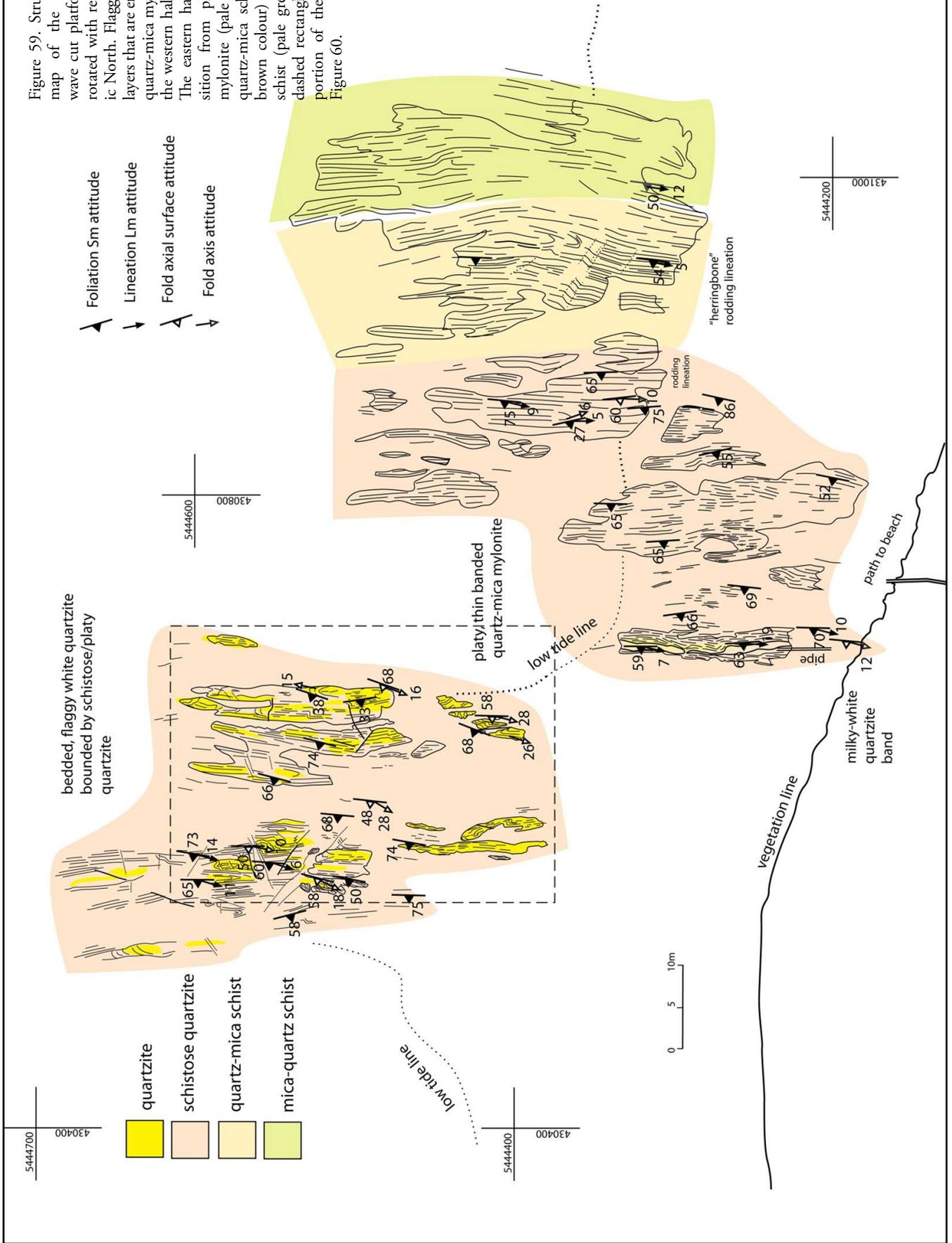


Figure 58. East Ulverstone wave cut platform structural map on a georeferenced Google Satellite image base. The western platform (left side of image) is dominated by bodies of thicker bedded quartzite containing asymmetric fold pairs. These are enveloped by platy quartz mylonites and schistose quartzites. The eastern side (right side of image) shows a transition from platy, thin-banded, quartz-mica mylonite to quartz-mica schist on the very eastern part of the platform. This represents a strain transition towards the non-exposed contact with the H-G Forth Metamorphic Sheet.

Figure 59. Structural form line map of the East Ulyerstone wave cut platform. The map is rotated with respect to magnetic North. Flaggy white quartzite layers that are enveloped by platy quartz-mica mylonites dominate the western half of the outcrop. The eastern half shows a transition from platy quartz-mica mylonite (pale fawn colour) to quartz-mica schist (pale yellow brown colour) to mica-quartz schist (pale green colour). The dashed rectangle is an enlarged portion of the map shown in Figure 60.



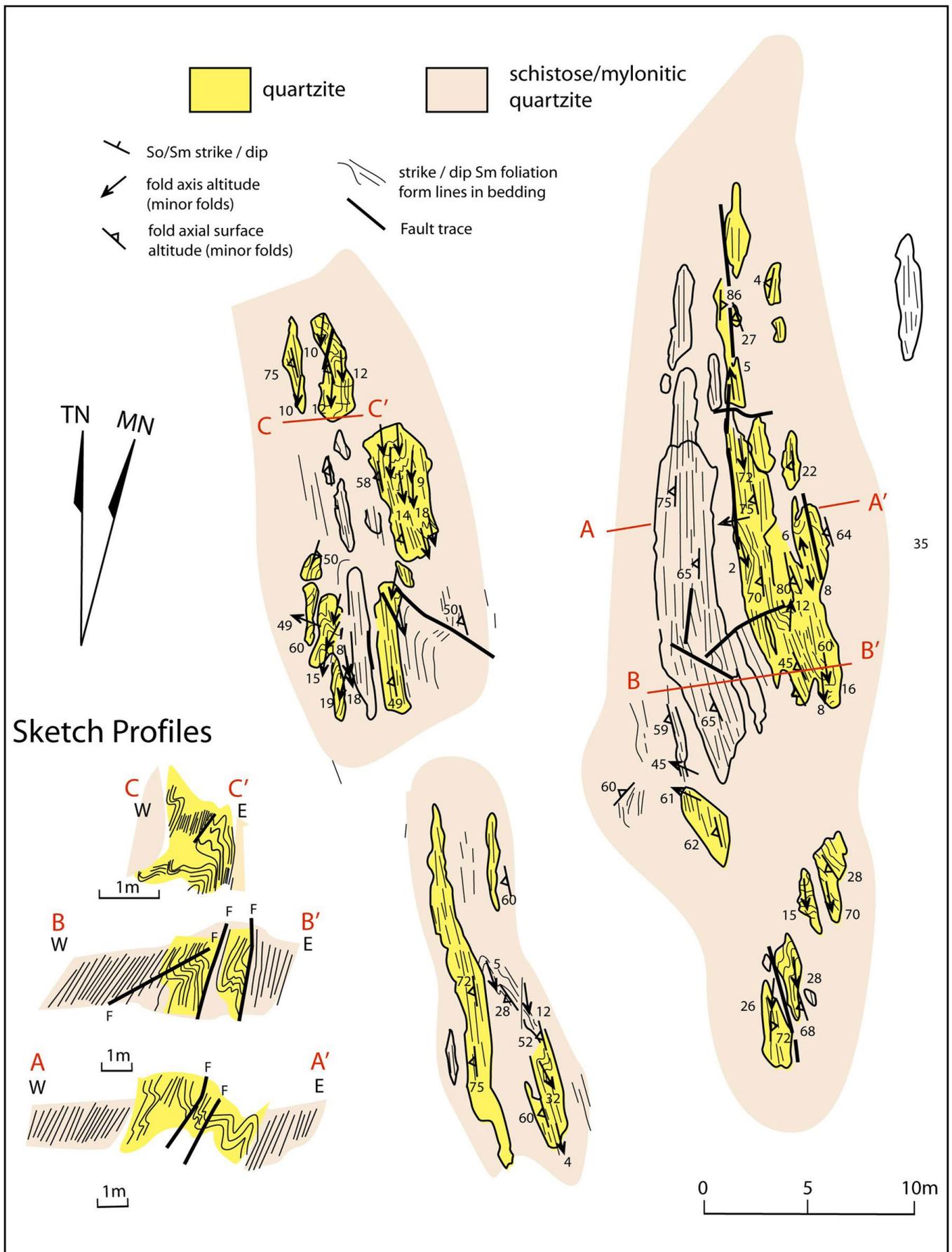
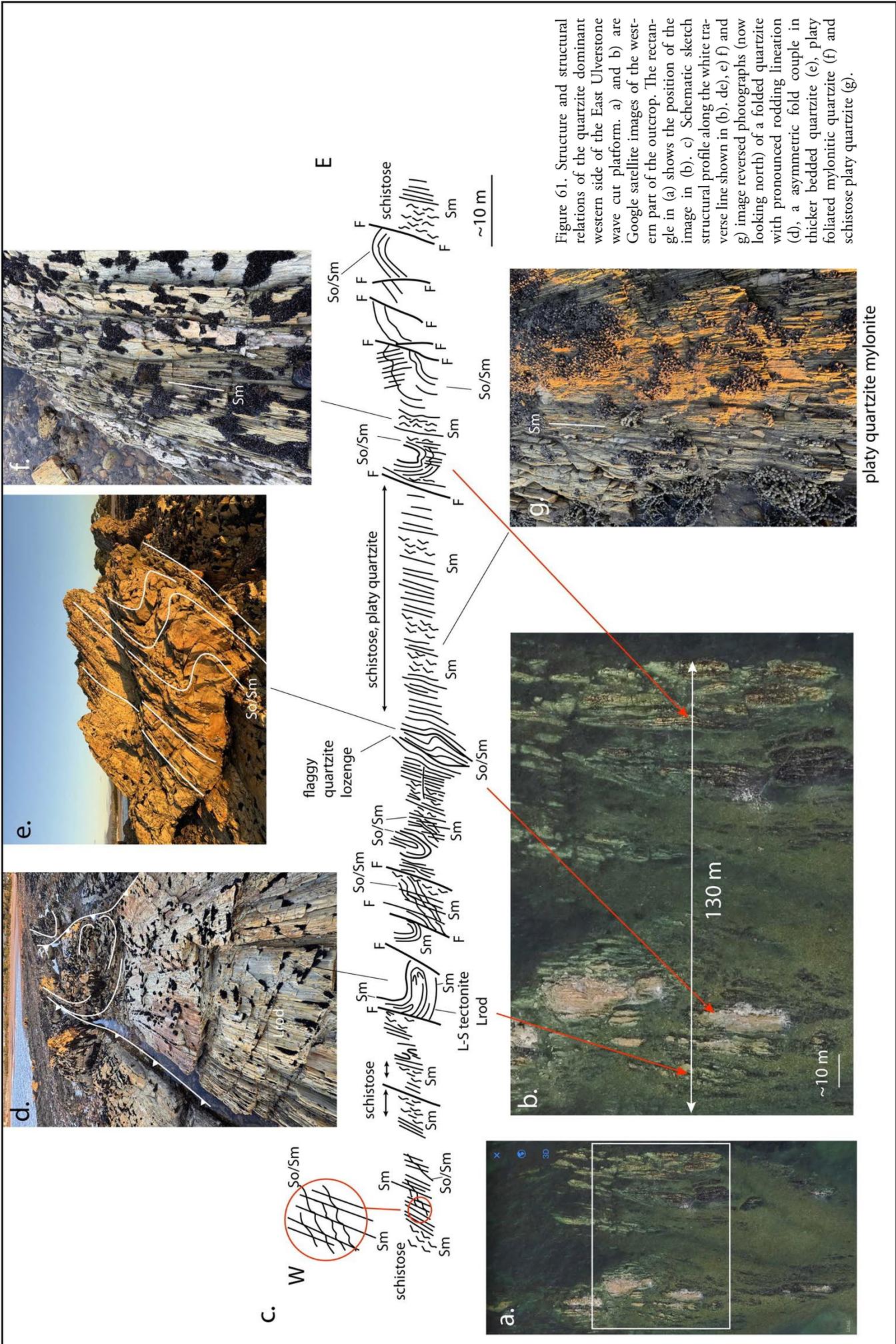


Figure 60. Map and structural profiles of the quartzite outcrops along the western side of the East Ulverstone coastal platform shown in Figure 59 (dashed rectangle). Structural profiles A-A', B-B' and C-C'' are shown at the bottom left. The profiles show thicker bedded quartzite lozenges hosting S-vergence asymmetric fold pairs. The quartzite is enveloped by schistose quartzite and quartz mylonite.



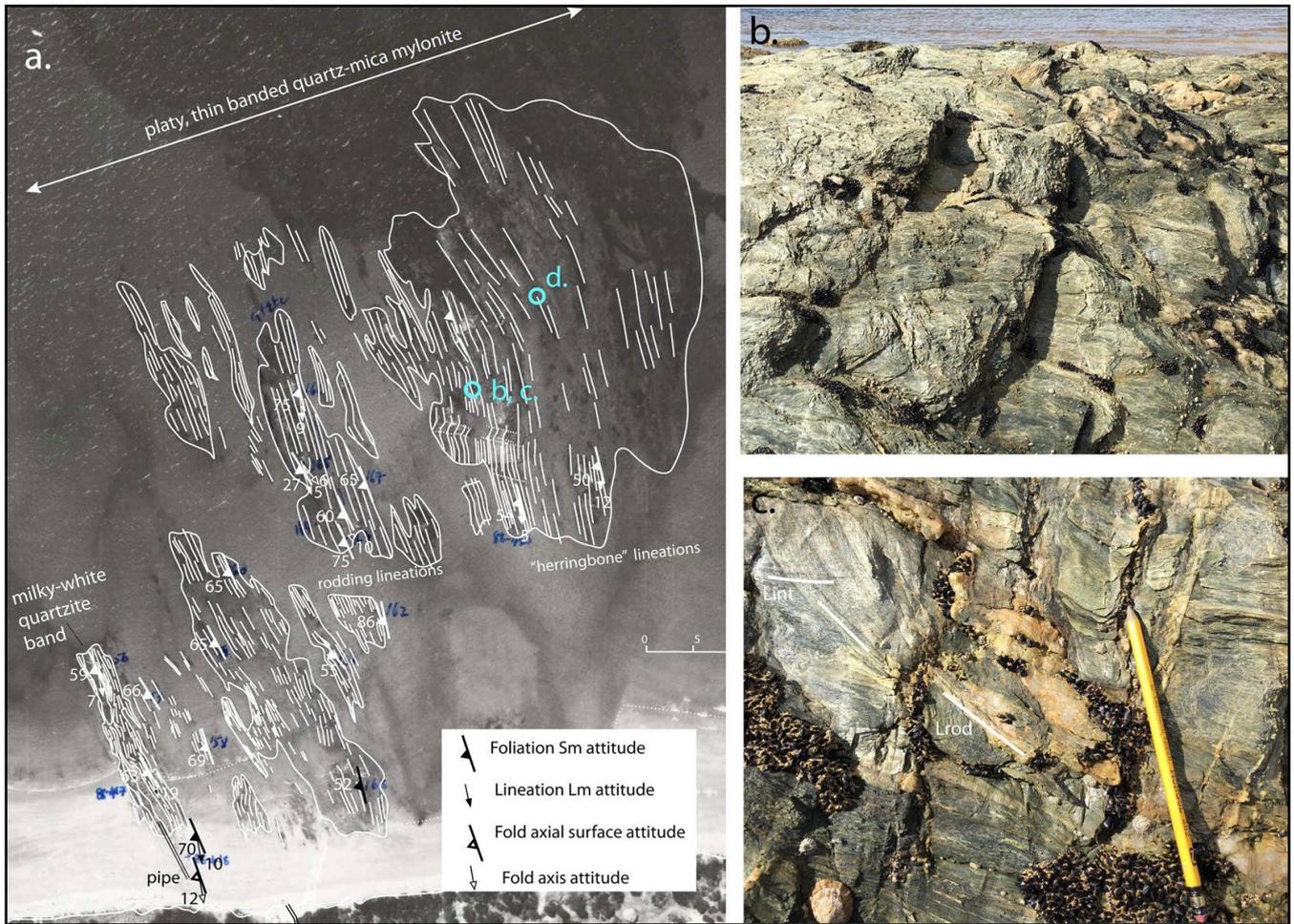


Figure 62. Structural and fabric relationships in the East Ulverstone wave cut platform. This represents a fabric transition at the base of the Ulverstone L-G Metamorphic Sheet towards the underlying, non-exposed interface with the Forth Metamorphic Sheet. a) Structural form line map of the beach outcrops at low tide on a black/white air photo base. Blue circles show the approximate locations of the outcrop photographs b and c. Blue circle d is the location of Figure 63. b) and c) are photographs of schistose rodding fabrics in thin, platy quartz mylonites. c) An enlarged view of the foliation Sm plane showing an early intersection lineation Lint defined by compositional banding streaking-traces overprinted by a developing rodding fabric in isoclinally folded quartz veins.

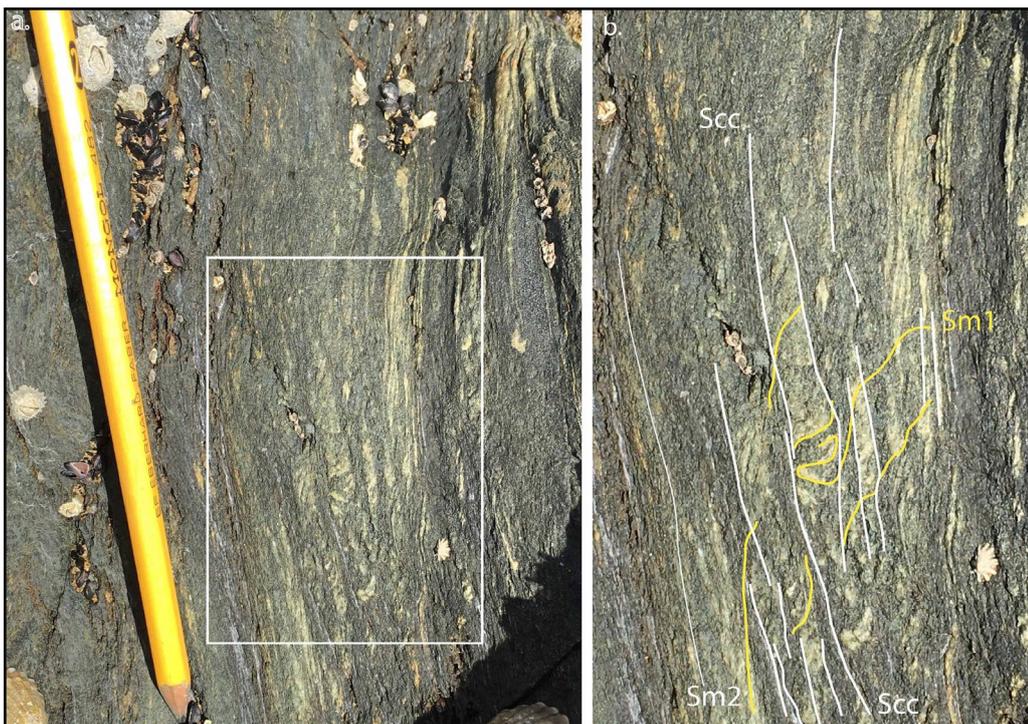


Figure 63. Mica-quartz schist on the eastern flank of the East Ulverstone Beach outcrops. The dominant foliation Sm is a compound foliation with sub-parallel Scc and crenulation of the first foliation Sm1. b) is an enlargement of (a).

### 3.1.6 Nature of Fabrics

#### 3.1.6.1 Quartzites

Foliated, flaggy quartzites and deformed quartzite pebbles of the deformed pebble conglomerate show partial to extensive quartz recrystallisation typical of deformation during greenschist facies metamorphism (Figure 64). Spry and Burns (1972) undertook extensive studies on the quartz fabrics within deformed quartzite pebbles of the Ulverstone Metamorphic Sheet in an attempt to relate pebble shape with the quartz shape fabrics and crystallographic preferred orientation. Most of the quartz fabrics exhibit mortar texture, where large undulose and lenticular quartz grains flattened and elongated within the foliation are surrounded by small, clear elongate quartz (Plates 1 and 2, Spry and Burns, 1972).

In outcrop the strongly deformed quartzites show an intense platy fabric (Figure 65), particularly those with a small percent mica component developing a schistose platy form (Figure 62b) as well as a pronounced rodding in places (Figure 66). The quartzites show strong mortar

texture and small elongate quartz grains (Photo 4, Plate 1, Spry and Burns, 1972).

#### 3.1.6.2 Quartz-mica Schist and Phyllite

The quartz mica schist, commonly transitional with schistose quartzite, occurs with an intense transposition foliation (schistosity) enveloping zones of isoclinal folding. Quartz augen of relict isoclinally folded and strung out quartz veins are also commonly enveloped by this schistosity (Figure 67).

Phyllites occur as localised layers 1) within high strain zones (see Figures 42, 43 and 44), and 2) interbedded with thin sand and silt layers in less deformed parts of the Ulverstone Metamorphic Sheet (Figure 68). These phyllites have a strong bedding parallel fabric (So/S1) defined largely by detrital muscovites (Figure 68).

### 3.2 Inland Part of the Ulverstone Sheet

The inland part of the Ulverstone Metamorphic Sheet is poorly outcropping with exposure limited to weathered road cuttings along Castra Road, McKennas Road and West Gawler Road (Figure 69).

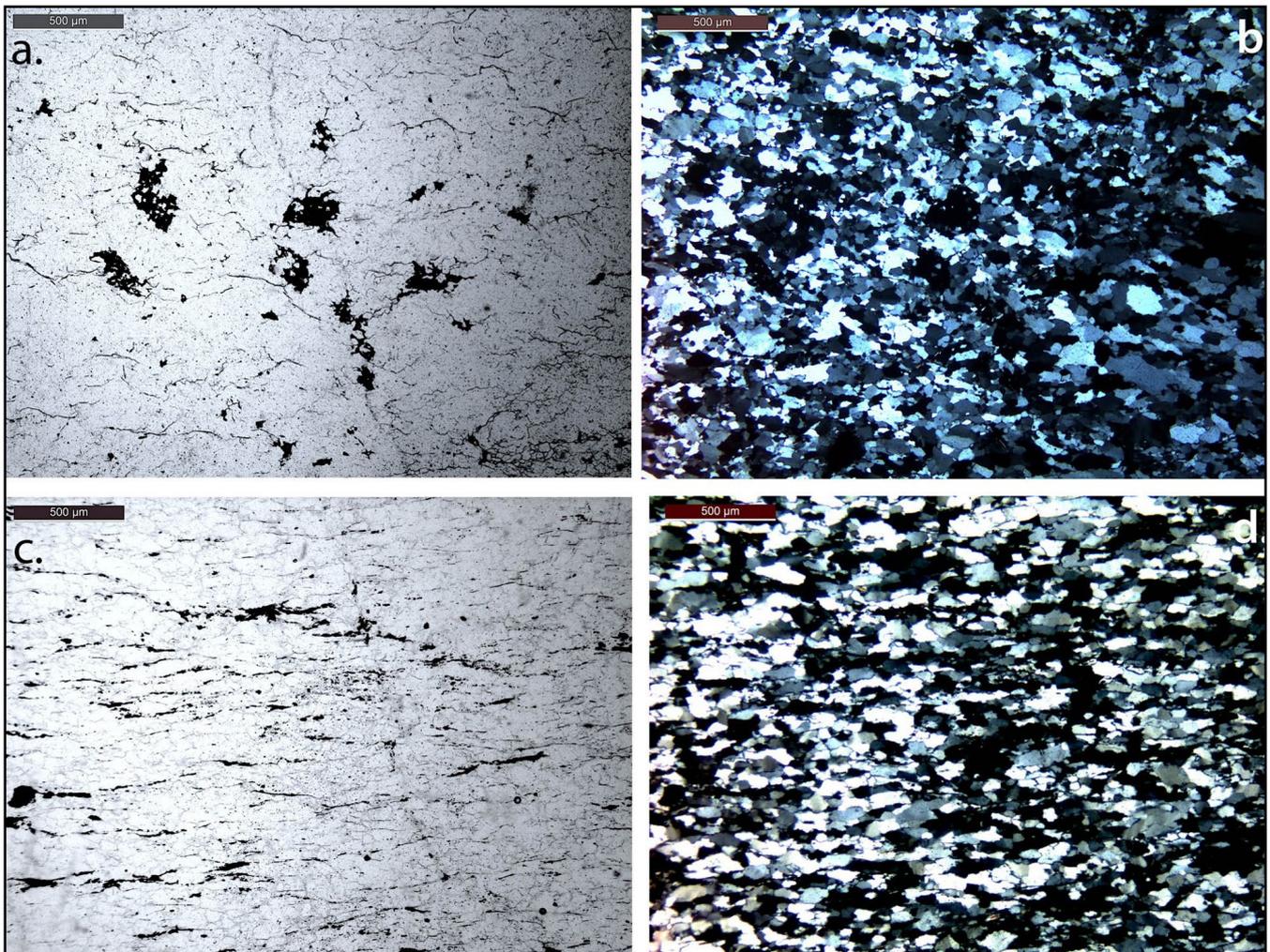


Figure 64. Seagull Islet quartzite microfabrics. a) PPL N section of sample P2 quartzite (normal to foliation and lineation) showing irregularly shaped, approximately ovoid skeletal opaques and short, discontinuous, irregular stylolitic cleavage/foliation traces. b) X nicols view of thin section in (a) showing equant quartz grains in a partially recrystallised quartz matrix. c) P section of sample P2 quartzite (normal to foliation and parallel to lineation) showing boudinaged and stretched, thin, elongated opaque trains parallel to a strong fabric fabric defined by quartz grain preferred orientation and subparallel closely spaced stylolitic cleavage/foliation traces. d) X nicols view of thin section in (a) showing strongly recrystallised quartz with a marked preferred shape elongation defining the foliation



Figure 65 (Left). Intensely foliated platy quartzite fabric with colour banding reflecting transposition of the original compositional layering. The platy quartzite defines higher strain zones that envelope the bedded quartzites at East Ulverstone Beach.

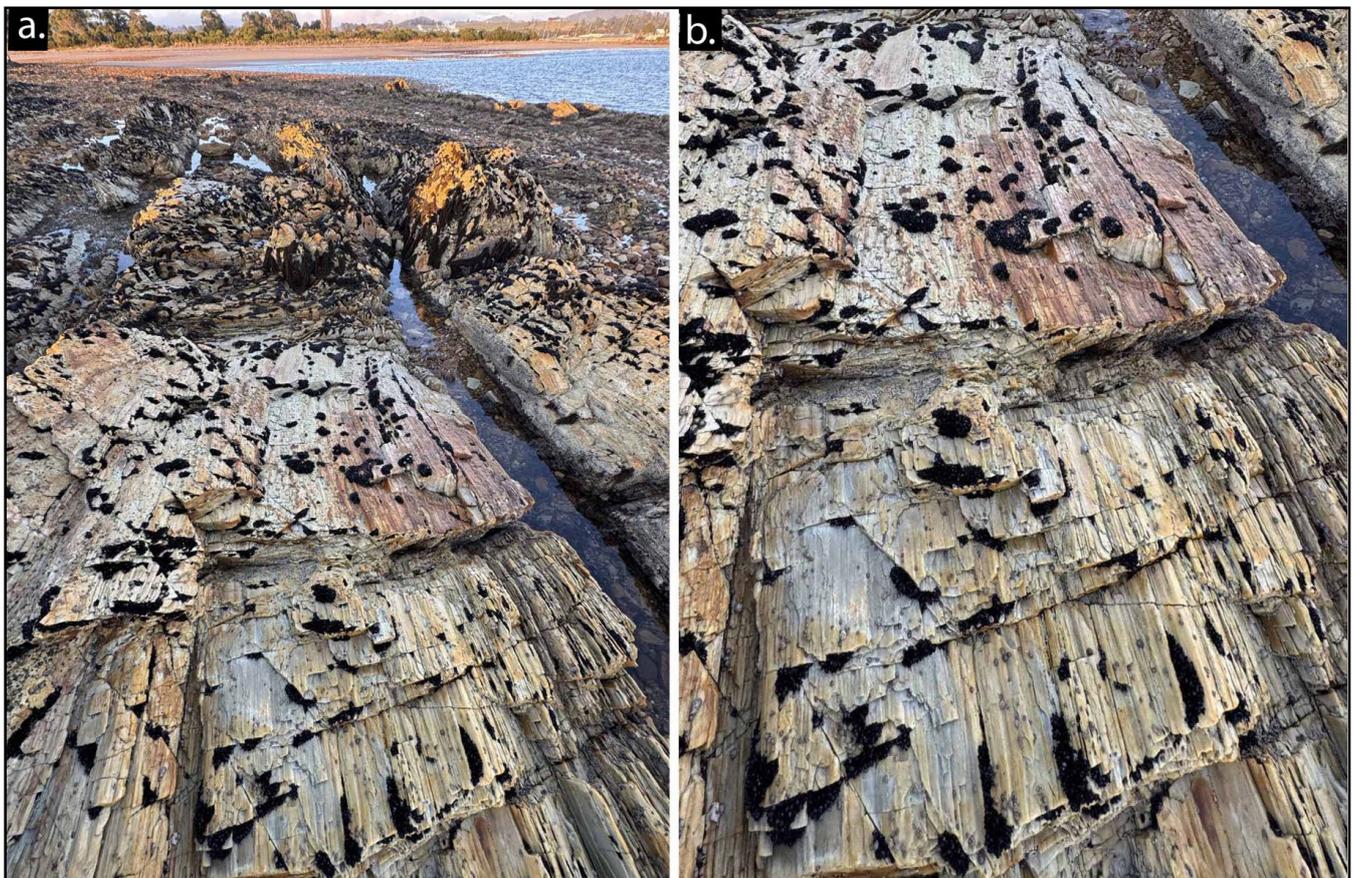


Figure 66. Rodding intersection lineation in quartzite, east Ulverstone Beach platform. The pronounced banding is due to intersection of compositional layering  $S_o/S_m$  with an intense foliation  $S_m$ .



Figure 67. Quartz vein augen in schistose quartzite/quartz-mica schist. Road cutting on West Gawler Road (Station DG25-55). a) Schistose foliated quartzite with intense transposition layering Sm enveloping 1) folded zones with isoclinal folds in transposed layering Sm1, and 2) quartz vein augen. b) and c) close ups of the quartz vein augen.

Outcrops along the West Gawler and McKennas Roads (West Gawler region, Figure 69) are mostly weathered schistose quartzite and quartz-mica schist with occasional thin quartzite layers. They show an intense, dominant transposition foliation Sm with an earlier fabric preserved in the shadow zones around quartz augen and within zones of isoclinal folding (Figure 67). These lithologies and intense foliation most likely occupy the largely now eroded and covered parts of the coastal exposures between Picnic Point and East Ulverstone (see Figures 6 and 7).

The Castra Road cuttings near Abbotsham (Abbotsham region, Figure 69), now extremely weathered, show refolding and development of multiple fabrics within the

west-dipping panel of the Ulverstone Metamorphic Sheet along the western limb of the Devonian Abbotsham Anticline. Upright to steeply west dipping F3 folds re-fold a series of tight to isoclinal folds within So/Sm with an axial surface crenulation cleavage Scc2 (Figure 70). The refolding is approximately coaxial along a northwest-southeast plunge trend, with the F3 folds largely plunging to the southeast (Figure 70). These have an axial surface crenulation cleavage Scc3 (Figure 71). The F2 folds mostly plunge to the west-northwest or to the west and show variable plunges and curved hinge lines. The coaxial nature of the refolding once again suggests progressive deformation in simple/general shear. These are similar to the structural relationships observed in the quartzites of the Seagull Islet macro lozenge (see Section 3.1.2).

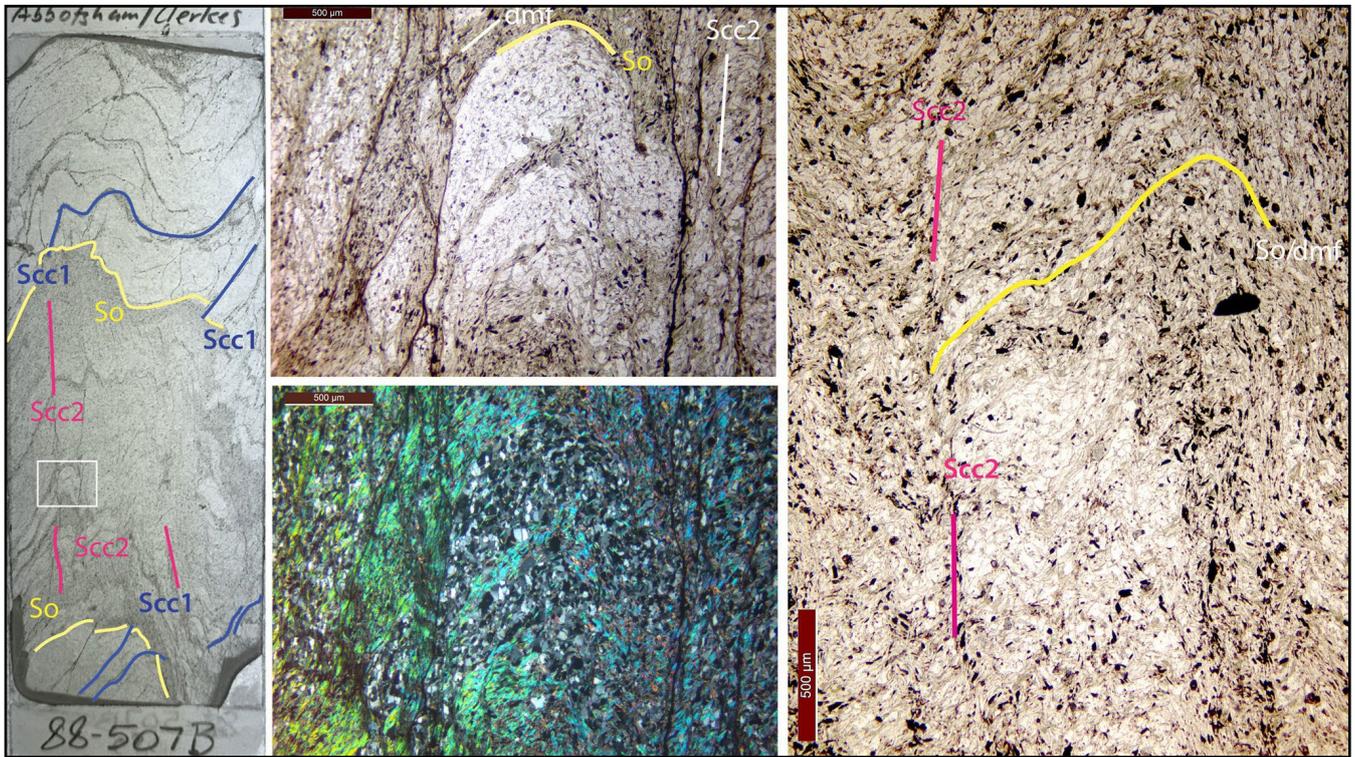


Figure 68. Fabric relationships within the Ulverstone Metamorphic Sheet at Abbotsham (DG88-507 location). a) Thin section photograph showing folded So/Sm layering (yellow traces) and multiple cleavages including Scc1 (primary crenulation cleavage) and Scc2 (discrete crenulation cleavage) axial surface to the folds in So (also see Figure 71). The white rectangle shows the position of (b). b) Photomicrograph of fold hinge in siltstone layer with limbs truncated and dissolved by a discrete crenulation cleavage. dmf: detrital mica fabric. PPL c) Nicols photomicrograph of (b) showing the very high proportion of detrital muscovite. d) Enlarged view of the microfabric showing a strong detrital mica fabric (dmf) at very low angle to sedimentary layering. Bedding So is highlighted by the silty layer (photo centre).

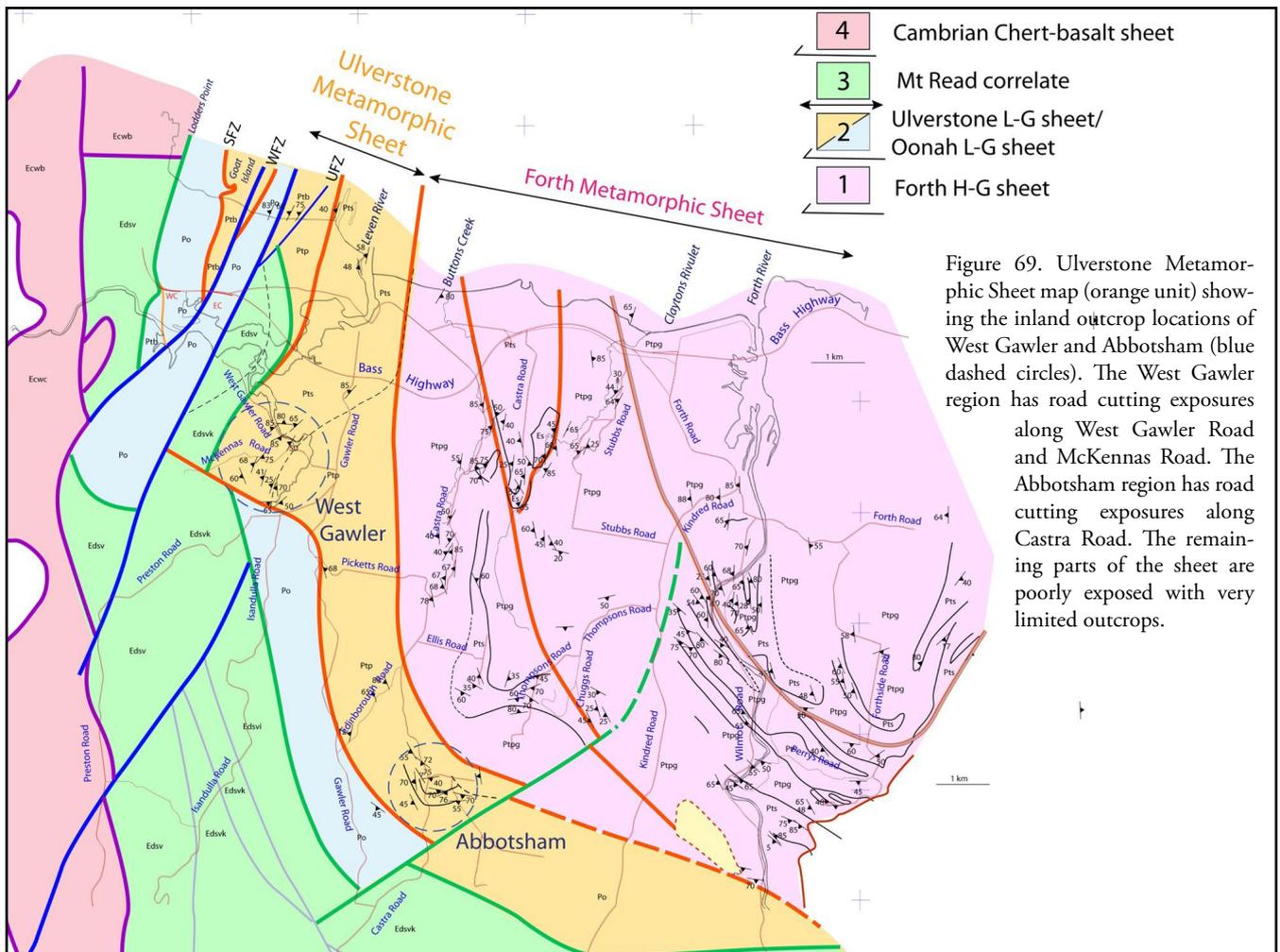


Figure 69. Ulverstone Metamorphic Sheet map (orange unit) showing the inland outcrop locations of West Gawler and Abbotsham (blue dashed circles). The West Gawler region has road cutting exposures along West Gawler Road and McKennas Road. The Abbotsham region has road cutting exposures along Castra Road. The remaining parts of the sheet are poorly exposed with very limited outcrops.

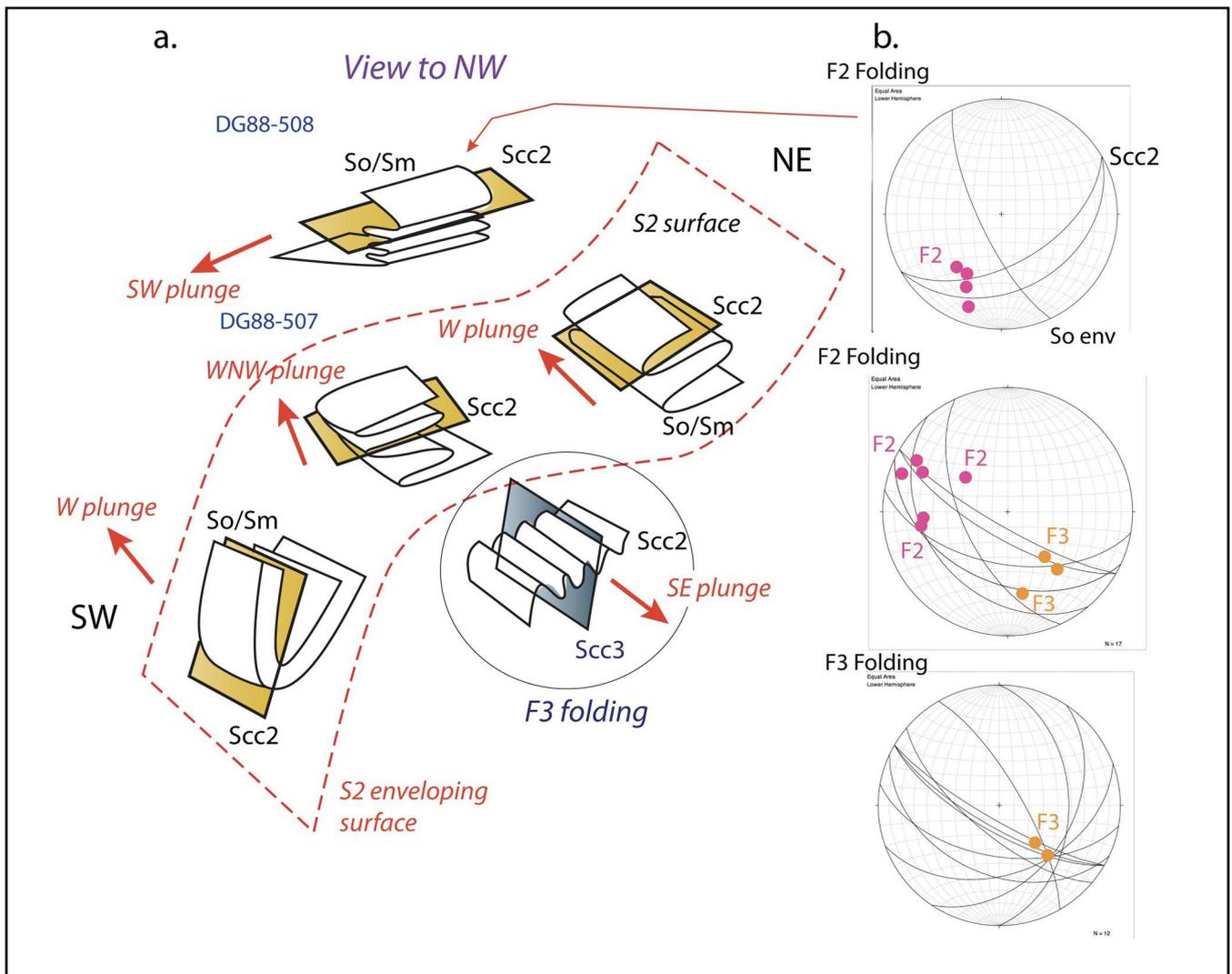


Figure 70. Structural relationships in the Castra Road cuttings near Abbotsham. a) 3D diagrammatic sketch of refolding and overprinting relationships viewed to the northwest. Meso-fold plunges are shown by the red arrows. The crenulation cleavage Scc2 is shown by the brown surfaces and the crenulation cleavage Scc3 by the grey surface. b) Stereonets show the fold attitudes for both F2 and F3 folds. Pink dots are F2 fold axes and orange dots are F3 fold axes.

#### 4.0 WEST ULVERSTONE IMBRICATE ZONE

The West Ulverstone Imbricate Zone (Figures 72 and 73) is a stacked, west-dipping series of fault-bounded slices involving the low-grade mudstone-sandstone sequence Oonah Formation correlate (Po), a basal deformed pebble conglomerate of Oonah Formation correlate (Ptb) and a *mélange* of Togari Group (Burns, 1964; Berry et al., 1990; Berry and Gray, 2001; Foster et al., 2005; Seymour and Vicary, 2014). The deformed pebble conglomerate of the Ulverstone Metamorphics has been reinterpreted as a metamorphosed greenschist facies, high strain slice of the Oonah Formation correlate based on a Neoproterozoic zircon population within the conglomerate matrix (sample G472429) from southwest side of Goat Island (Mulder et al., 2018, fig.8c).

The West Ulverstone Imbricate Zone represents the upper imbricated part of the Ulverstone Metamorphic Sheet repeated by Devonian east-directed reverse faulting. It

is treated and discussed in two outcrop domains. These include: 1) a coastal segment, and 2) a structural profile along the Bass Highway. The coastal segment is divided into two fault slices that represent repeated parts of the Oonah Sheet and Ulverstone Metamorphic Sheet contact (Figures 72 and 73). The nature of the contact is different and is reactivated and/or overprinted by younger Devonian thrusting and reverse faulting.

**Fault Slice 1:** extends from Westbank Siding to the Westbank Fault Zone (Figure 73). It includes on the west the Westbank Siding Oonah L-G sandstone-mudstone slice emplaced over deformed pebble conglomerate along the Singleton Fault. The slice shows significant Devonian reactivation.

**Fault Slice 2:** extends from the Westbank Fault Zone to the Ulverstone Fault Zone (Figure 73). It includes the West Ulverstone L-G Oonah mudstone-sandstone slice in HSZ contact with the pebble conglomerate and schist/phyllite of the Ulverstone Metamorphic Sheet.

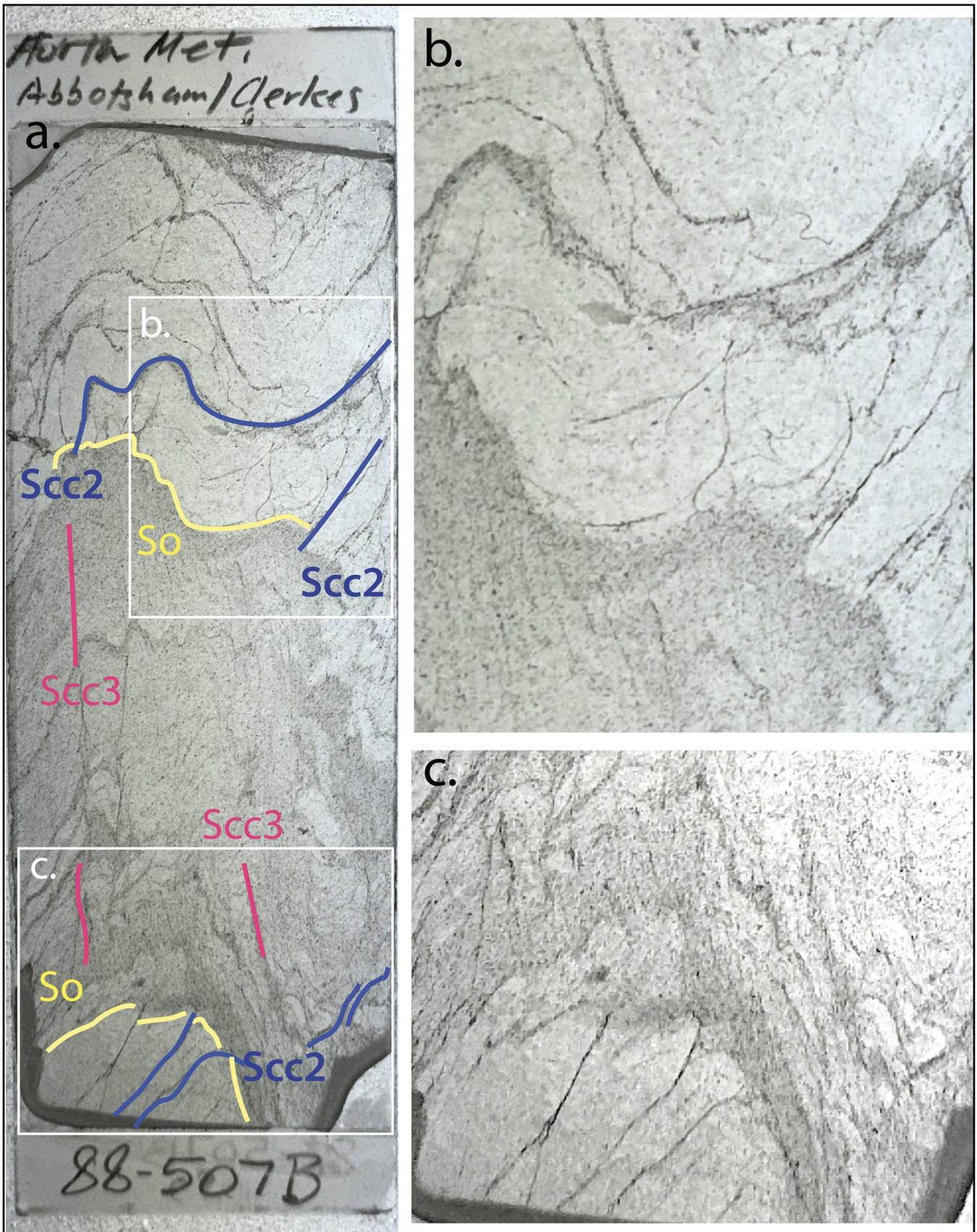


Figure 71. Folded siltstone-phyllite layering with multiple fabrics within the Ulverstone Metamorphic Sheet at Abbotsham (DG88-507 location). a) Annotated thin section photomicrograph. Thin section width is 2.5 cm. b) and c) are enlarged parts of the thin section photograph.

*So*: bedding; *Scc2* and *Scc3* are discrete crenulation cleavages that have been reclassified (compare with Figure 68) to satisfy the outcrop relationships in Figure 70 above.

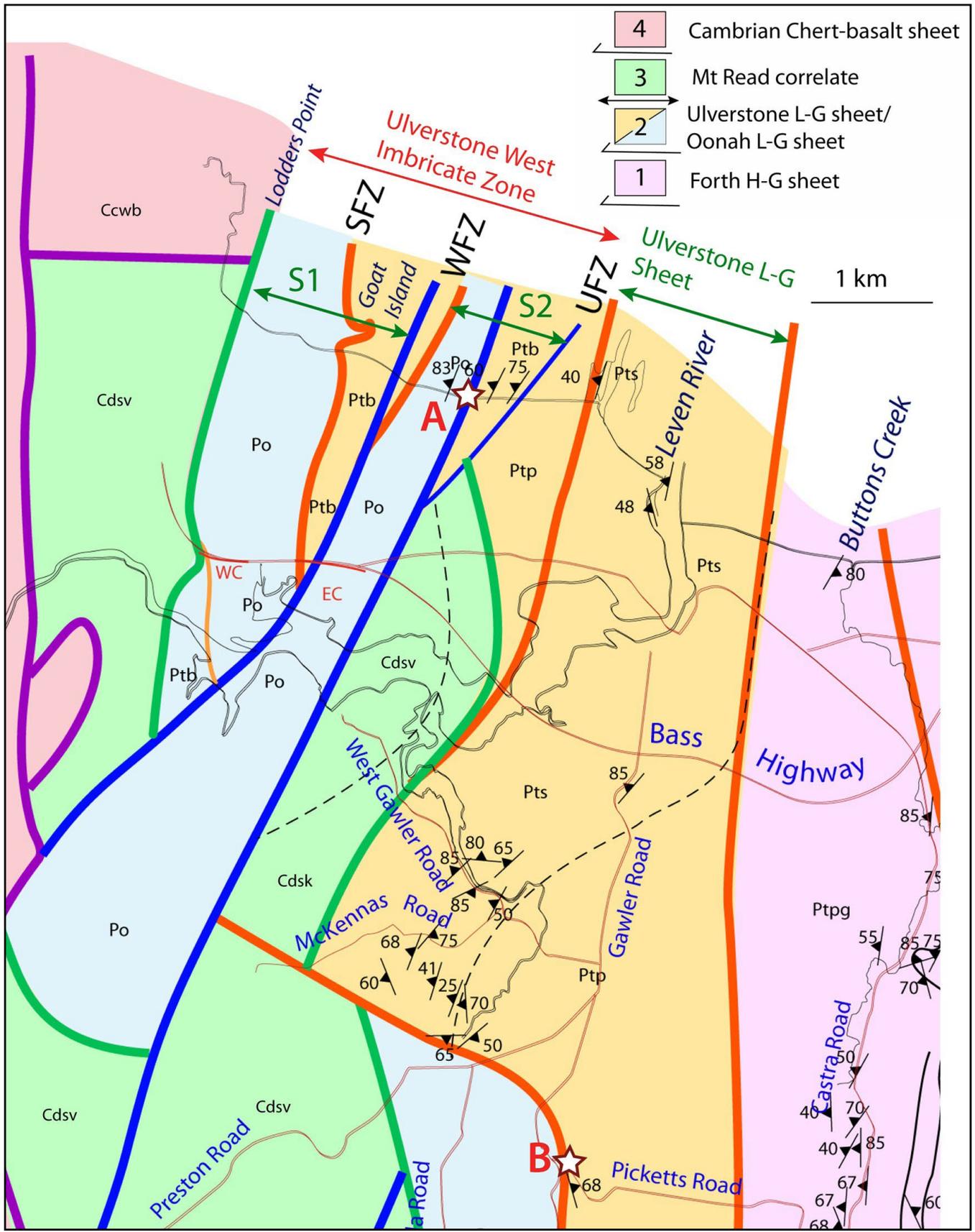


Figure 72. West Ulverstone Imbricate Zone map showing the major fault traces and structural slices/sheets. The fault slices include the Oonah L-G slices (pale blue), the Ulverstone L-G slices (pale orange), the Forth H-G Sheet (pink), the Luina Sheet (Cambrian chert-basalt obduction sheet) and the Mt Read Volcanics units (green). Bright green fault traces are Middle Cambrian extensional faults. Blue fault traces are Devonian thrust-reactivated Middle Cambrian extensional faults. Red fault traces are Early Cambrian thrust faults/HSZ commonly with brittle fault over-prints. The purple fault traces are the Late Cambrian obduction faults bounding the Luina Sheet. Sheet stacking is shown with stacked units 1, 2 and 4 from lowest to highest. Unit 3 represents the Mt Read Volcanic graben fill. Star location A: West Ulverstone beach Oonah Sheet\_Ulverstone Sheet contact. Star location B: Picketts Road Oonah Sheet\_Ulverstone Sheet contact.

Po: Neoproterozoic Oonah Formation. Ptb: Neoproterozoic pebble conglomerate. Ptp: Neoproterozoic pelite (phyllite). Pts: Neoproterozoic schistose quartzite. Ptpg: Mesoproterozoic schist. Cdsv: Cambrian marine volcano-sedimentary and sedimentary sequence. Cdsvk: Cambrian volcanoclastic sedimentary and volcanic sequence (andesitic lavas). Ccwb: Early Cambrian allochthonous chert-basalt sequence.

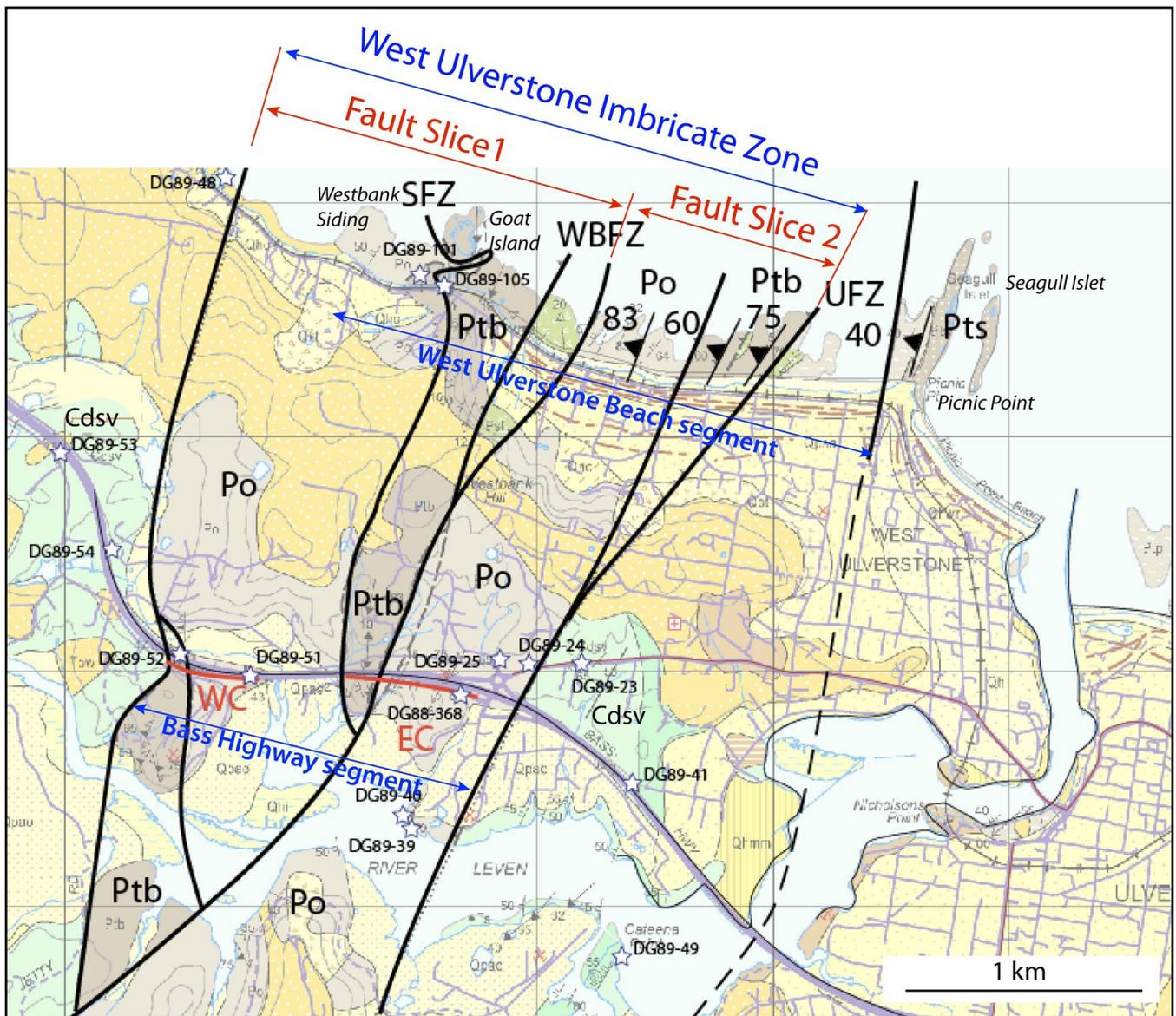


Figure 73. West Ulverstone Imbricate Fault Zone map. The base map is from the Mineral Resources Tasmania 1:25,000 digital atlas. Major fault traces are highlighted by the black line traces and include the SFZ: Singleton Fault Zone, WBFZ: Westbank Fault Zone, and the UFZ: Ulverstone Fault Zone. Units 1 and 2 are fault slice packages made up of a structurally higher, less deformed Oonah mudstone-sandstone sequence overlying a basal high strain zone of deformed conglomerate, quartzite and quartz-mica schist, overlying a mélangé of Togari Group blocks in a scaly mudstone matrix.

The locations of the two major road cuttings on the Bass Highway shown by the red line traces and designated WC (West Cutting) and EC (East Cutting).

*Cdsv*: Cambrian marine volcano-sedimentary and sedimentary sequence. *Po*: Neoproterozoic Oonah quartzwacke turbidites. *Ptb*: Neoproterozoic deformed conglomerate (basal Oonah Formation). *Pts*: Proterozoic schistose quartzite

#### 4.1 Goat Island Slice (Fault Slice 1)

The Goat Island Fault Slice (Fault Slice 1) is exposed at low tide in the wave cut platform from Westbank Siding - Goat Island to the Westbank Fault Zone (Figures 73, 74 and 75). It is a fault slice made up of the low-grade Oonah Sheet on the west and the Ulverstone Metamorphic Sheet on the east with the Singleton Fault Zone as contact between the sheets (Figures 73 and 74). These are fault slices of the more extensive Oonah and Ulverstone Sheets (Figure 2) and respectively represent the hanging wall and footwall units of the Singleton Fault.

The outcrop trace of the Singleton Fault (barbed, red line trace, Figure 76) is as a steep-sided, tongue-like re-entrant within the overall steep, west-dipping fault. Very low grade Oonah sandstone and mudstone sequence (hanging wall) has been emplaced over Goat Island pebble conglomerate (footwall) (Figures 76 and 77). The sequence is overall moderately to steeply west-dipping with a zone of faults developed in the Oonah hanging wall at the mouth of the fault re-entrant (Figure 76). The footwall, although cut by the fault re-entrant, is folded at 150 m scale with a moderate to strong S2 foliation in the pebble conglomerate (Figure 77).

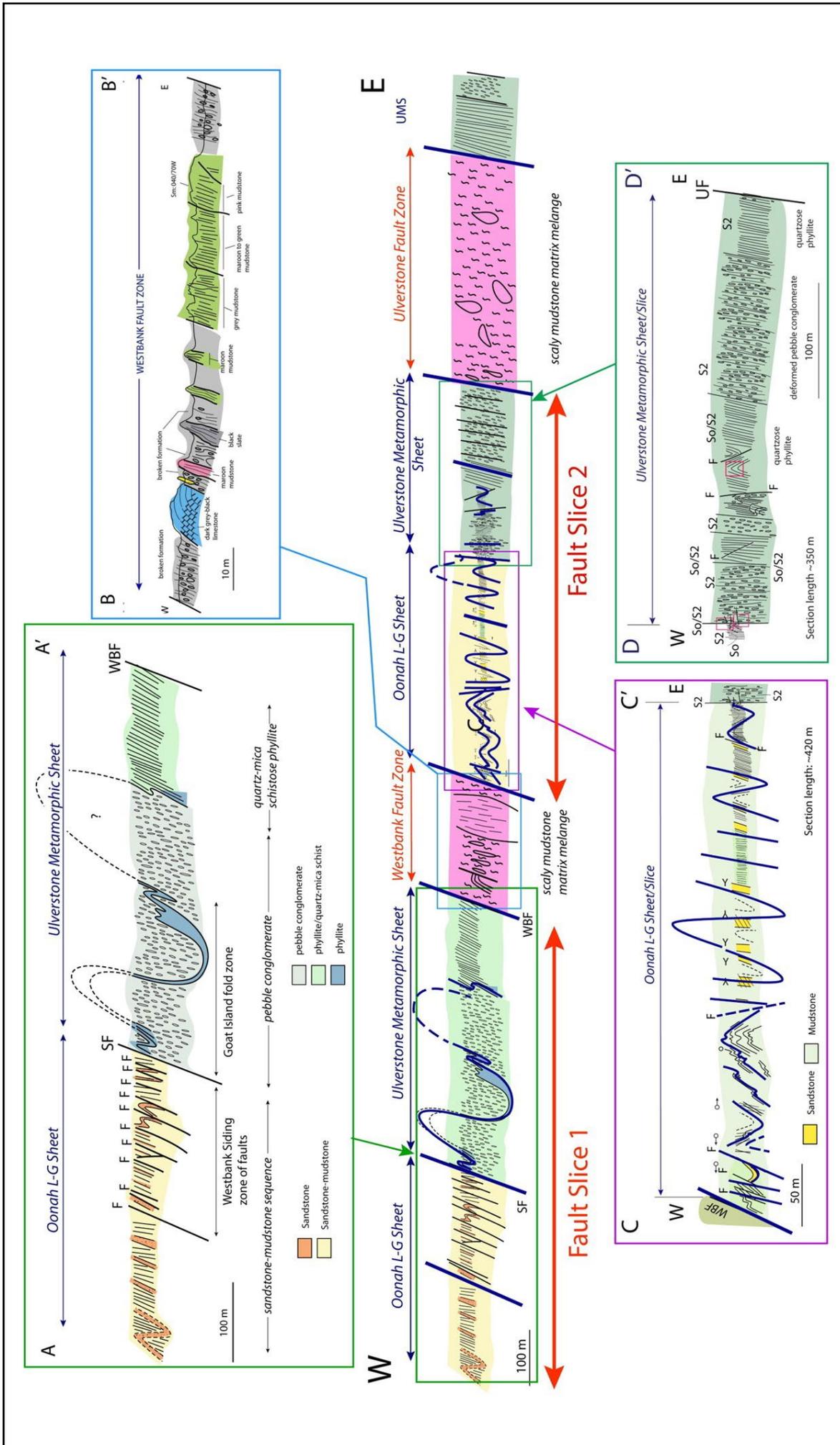


Figure 74. Regional structural profile across the West Ulverstone Imbricate Zone and the Ulverstone Metamorphic Sheet within two Devonian fault slices. The profile is based on E-W sections constructed along the coast for the West Ulverstone Beach segment (see Figure 2). Fault Slice 1 includes the Oonah Sheet slice at Westbank Siding and the Ulverstone Sheet slice at Goat Island separated by the Singleton Fault. Fault Slice 2 is bounded by the Westbank and Ulverstone Fault Zones and includes the Oonah L-G Sheet slice in contact with a slice of the Ulverstone Sheet. Profile A-A': Figure 77. Profile B-B': 131b. Profile C-C': Figure 106. Profile D-D': Figure 117.



Figure 75. Georeferenced ListMap Google satellite image of Goat island Fault Slice 1 including Westbank Siding- Goat Island coastal rock platform at low tide. The Singleton Fault (SF) is shown by the white line trace. Blue line traces are faults. Red line traces: So and So/Sm form line traces. Bedding attitudes in the Oonah Sheet are shown by strike/dip symbols. Foliation Sm attitudes in the Ulverstone Sheet are shown by the barbed strike/dip symbols.

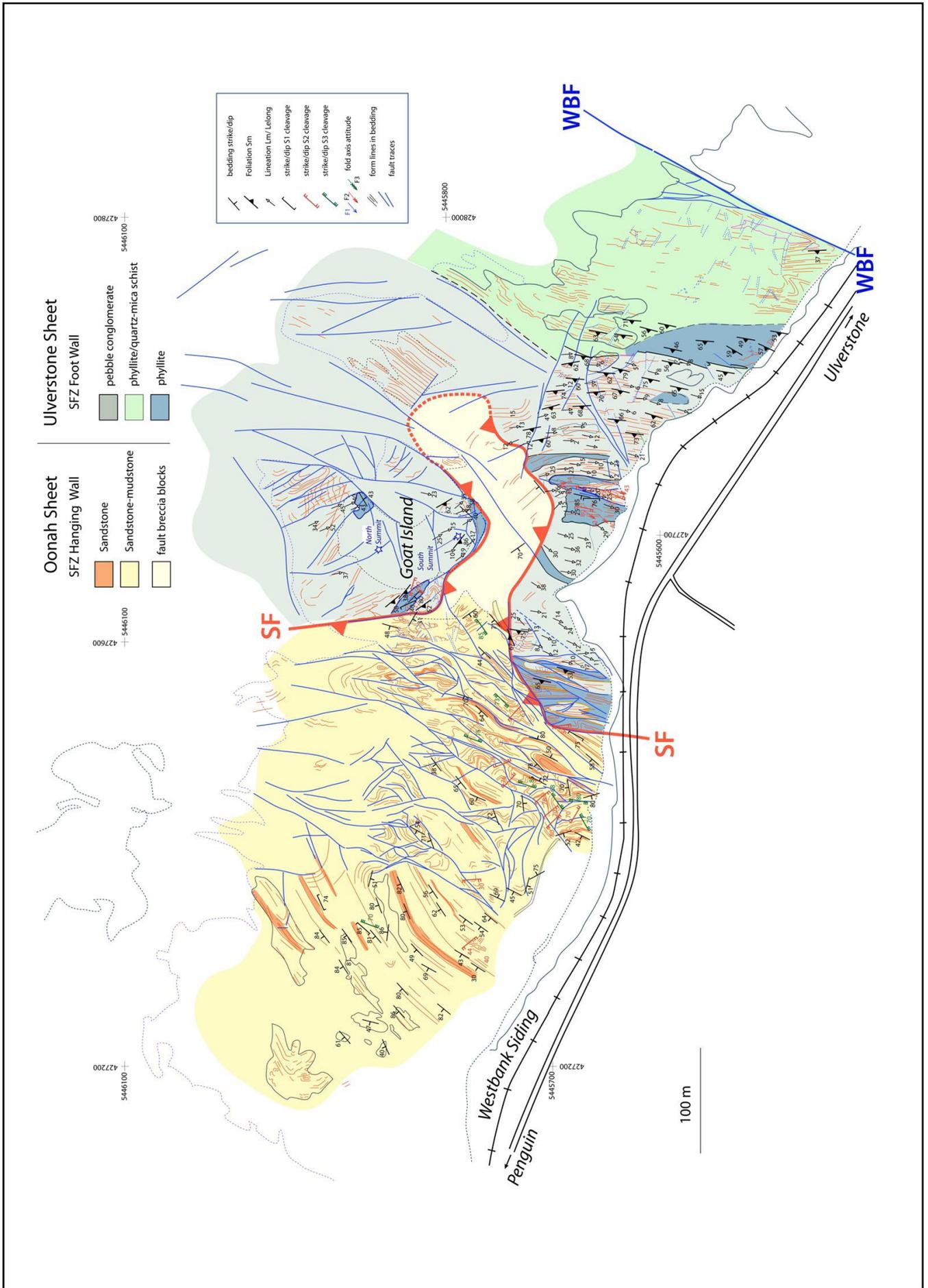


Figure 76. Structural lithological map of the Westbank Siding-Goat Island coastal segment.

The outcrop trace of the Singleton Fault (barbed, red line trace) appears as a steep-sided, tongue-like projection of very low grade Oonah sandstone and mudstone sequence (hanging wall) emplaced over Goat Island pebble conglomerate (footwall).

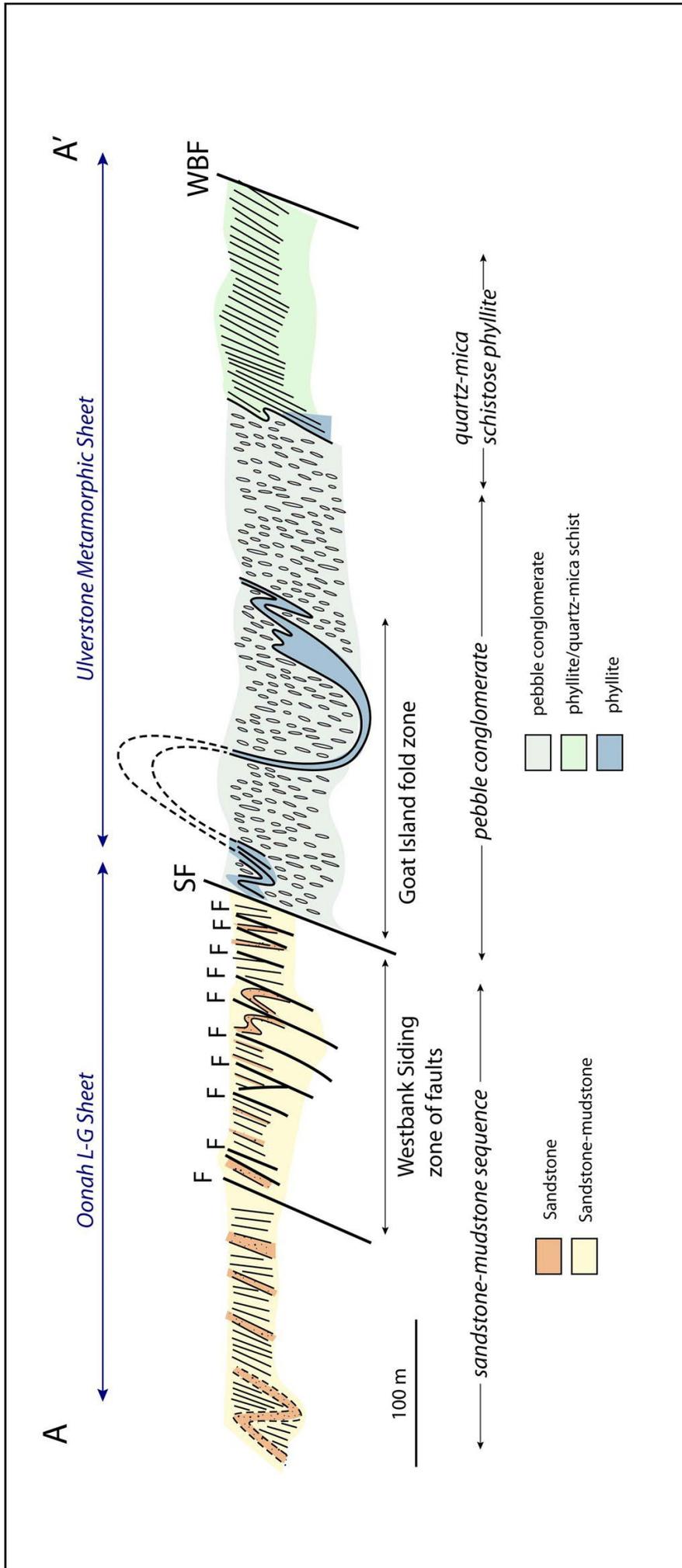


Figure 77. Goat Island structural profile A-A' from Westbank Siding to the Westbank Fault incorporating Fault-Slice 1 of the Coastal segment. SF: Singleton Fault. WBF: Westbank Fault.

#### 4.1.1 Hanging Wall Structural Relationships (Oonah Sheet)

Interbedded sandstones and mudstones of the Oonah Formation show strong faulting (Figures 78 and 79), fold interference patterns, local development of multiple crenulation cleavages and variable degrees of deformation (Figures 78 and 80). The sandstones have a spaced cleavage accentuated by alignment of quartz grains on weathered surfaces. This is in contrast to the quartzites of the Ulverstone Metamorphic Sheet (footwall) that have a strong foliation and lineation and show metamorphic grain growth

fabrics in thin section (see Figure 64 b, d).

Polydeformed segments appear to be controlled by meridional faults in a ~200 m zone adjacent to the Singleton fault (Figures 78 and 79). The first generation folds are re-folded by second and third generation folds in a 30 m zone between two of these faults (Figures 81, 82, 83 and 84). Crenulation cleavages occur as axial surface foliations associated with the later folds (Figures 80, 83 and 84). Kinks also complicate the outcrop pattern and occur in a NE-SW trending zone in the southern part of the exposure.

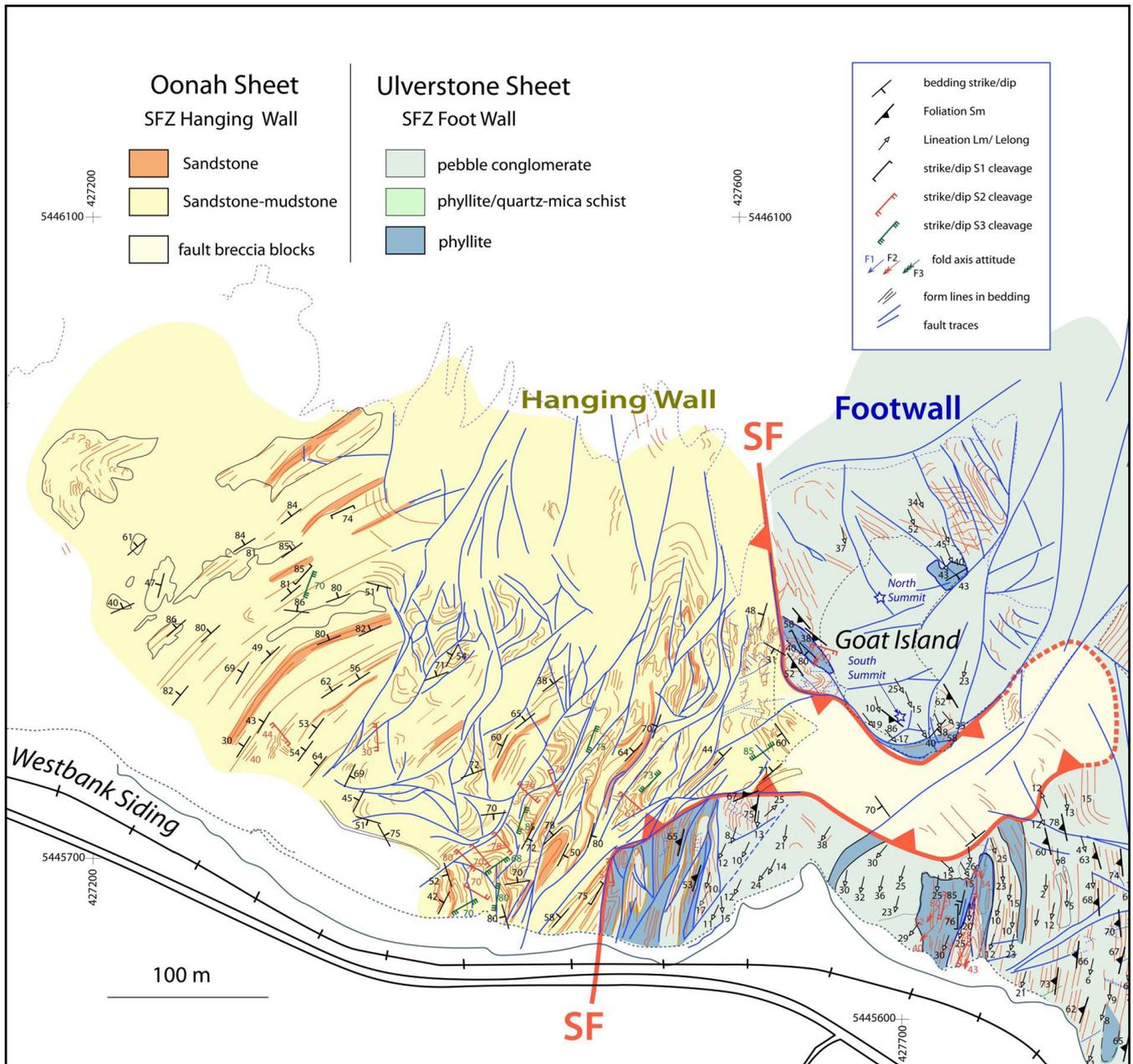


Figure 78. Structure map of the Oonah Sheet as hanging wall to the Ulverstone Fault. The structural character changes from homoclinal north-west dip with bedding and a slaty type cleavage on the west (opposite Westbank Siding) to a zone of marked faulting and poly-deformation with refolding and crenulation cleavages (blue line traces) on the east, adjacent to the Singleton Fault (SF).

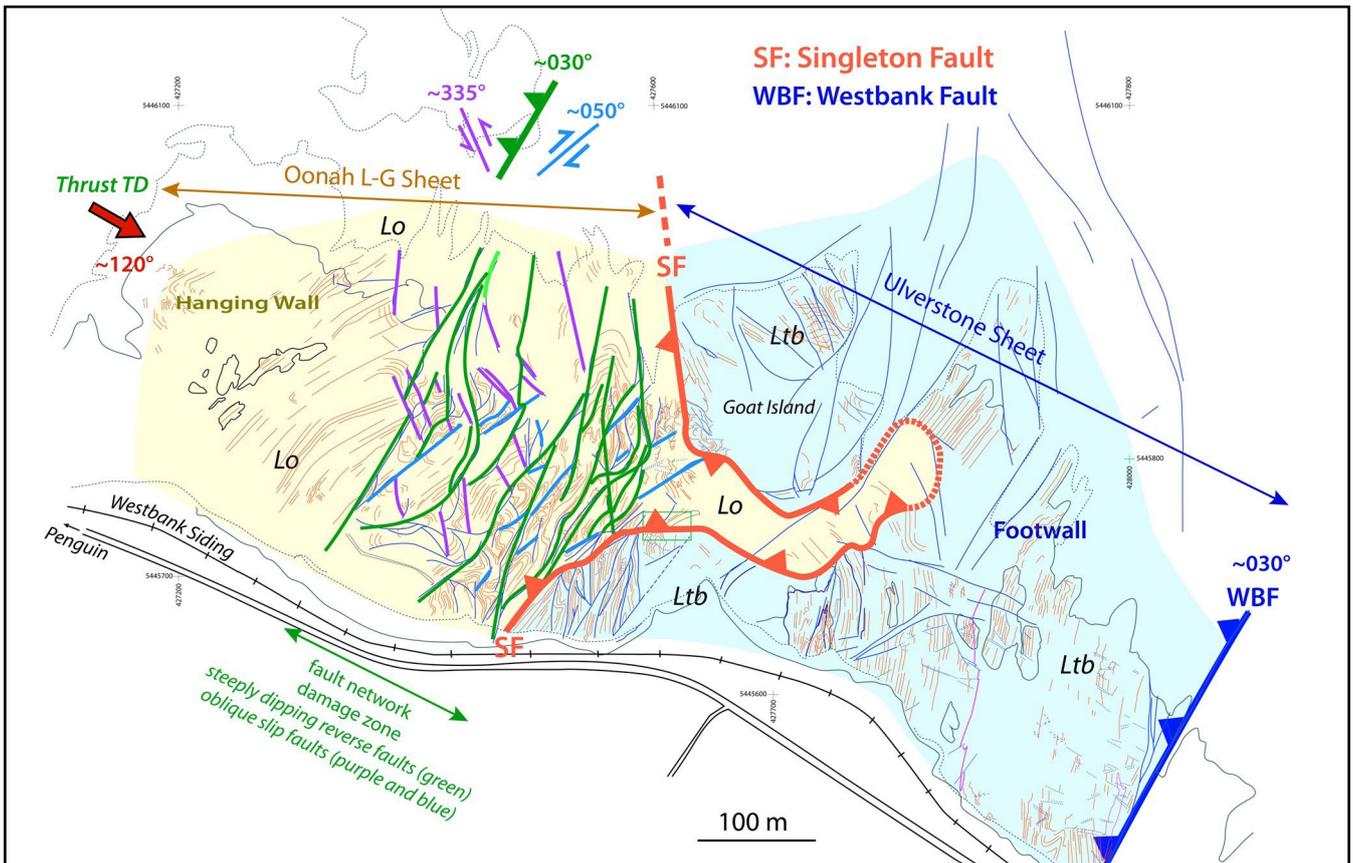


Figure 79. Fault relationship map within the Oonah L-G sheet showing a "log-jam" effect with faults largely developed in a ~200 m zone abutting a steep, footwall ramp within Goat Island conglomerate of the Ulverstone Metamorphic sheet. The ramp is part of the Singleton Fault shown by the red barbed line trace. Green lines depict the dominant fault set (~030° trending) with subsidiary fault sets (purple line traces: ~335° trending/ blue line traces: ~050° trending). The red arrow is the inferred thrust transport direction (~120°).

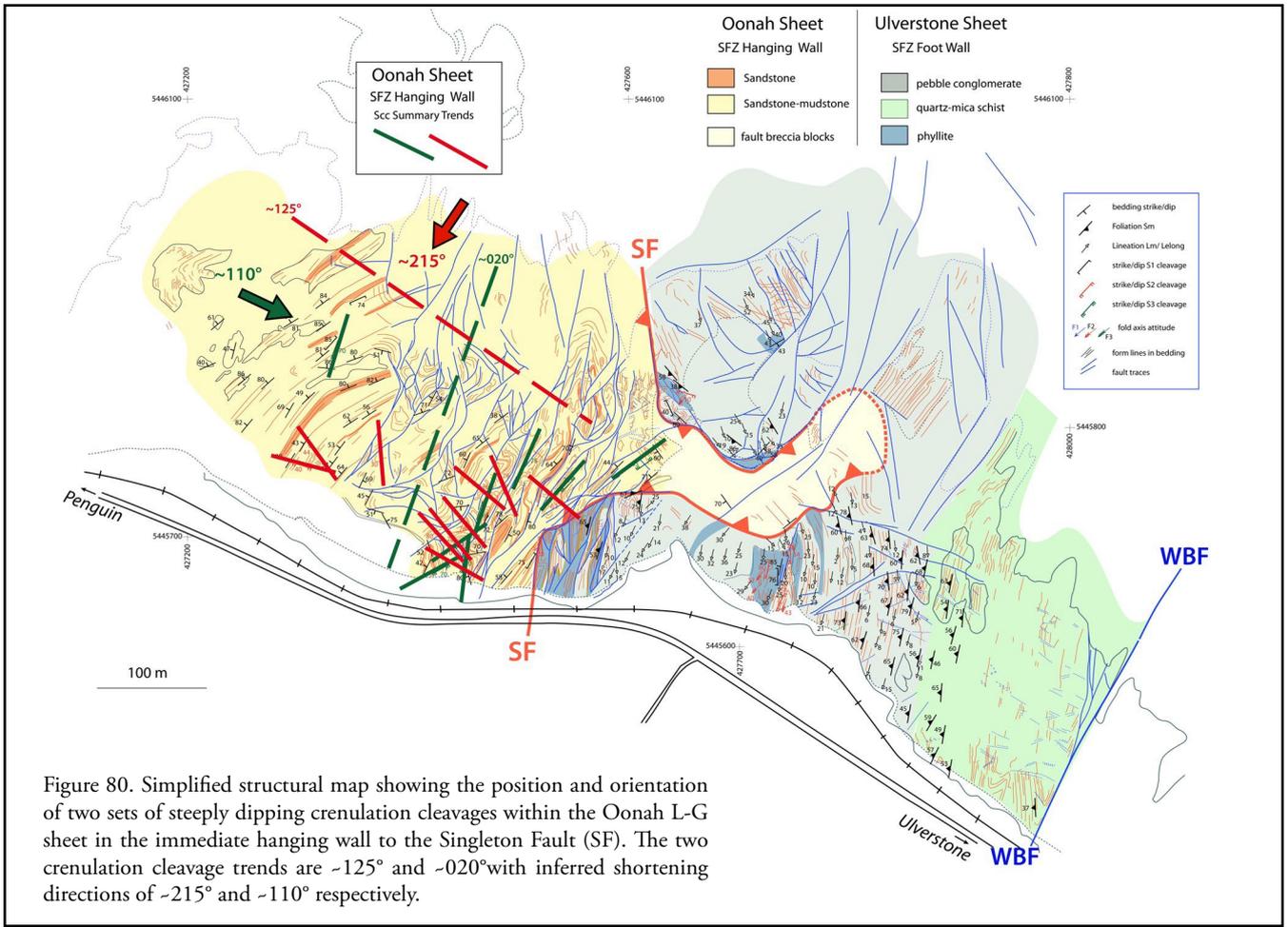


Figure 80. Simplified structural map showing the position and orientation of two sets of steeply dipping crumulation cleavages within the Oonah L-G sheet in the immediate hanging wall to the Singleton Fault (SF). The two crumulation cleavage trends are ~125° and ~020° with inferred shortening directions of ~215° and ~110° respectively.

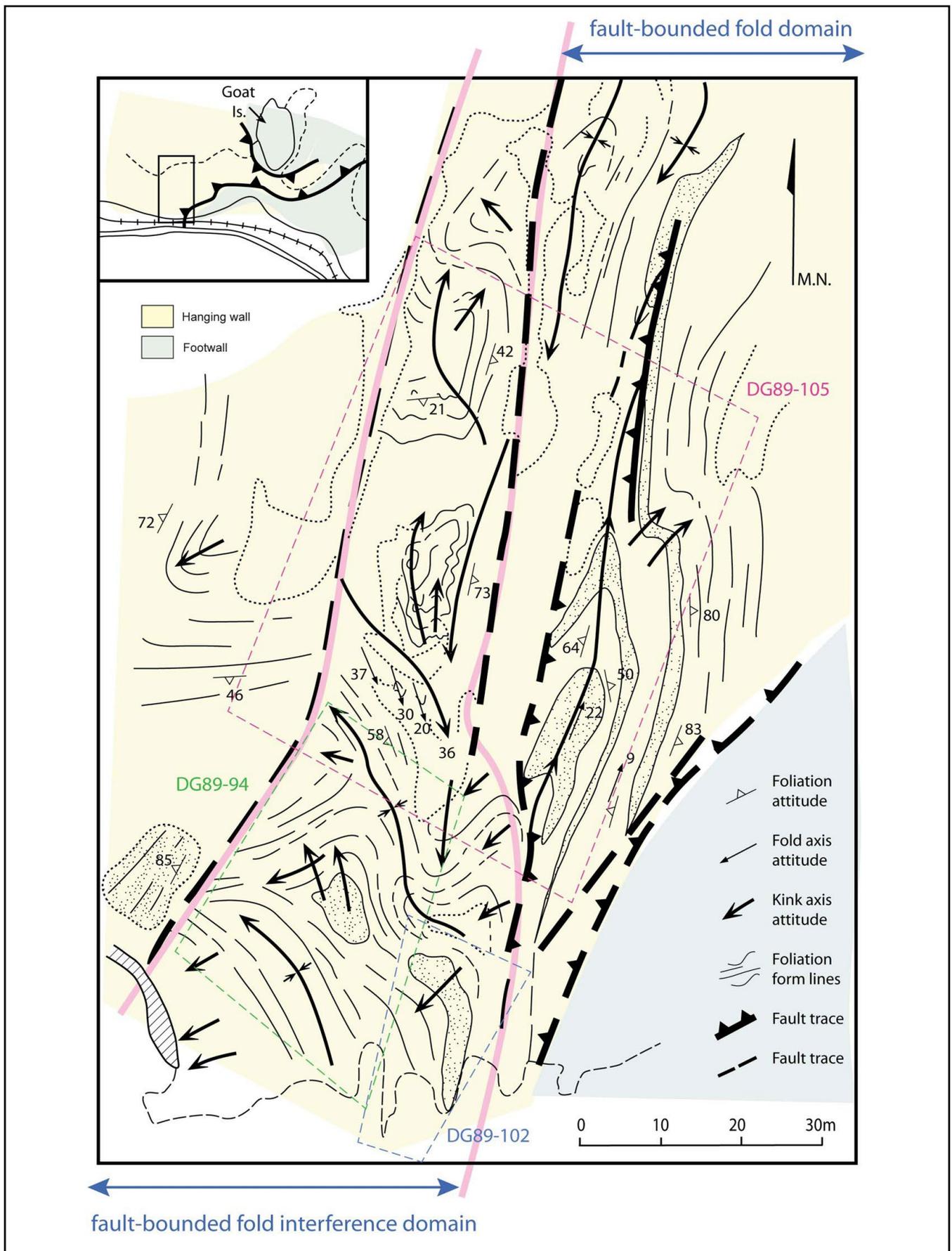


Figure 81. Simplified structural map of the Oonah L-G Sheet in the immediate hanging wall of the Singleton Fault. DG89-94 (green dashed polygon), DG89-102 (blue dashed polygon) and DG89-105 (pink dashed polygon) detailed structural sketch map locations are shown by the polygons with coloured dashed outlines (see map area outlines on georeferenced satellite image in Figure 82). Two structural domains are highlighted. These are 1) a fold-interference domain with both NE and NW- trending fold sets, and 2) a folded domain with the NE-trending fold set as dominant.

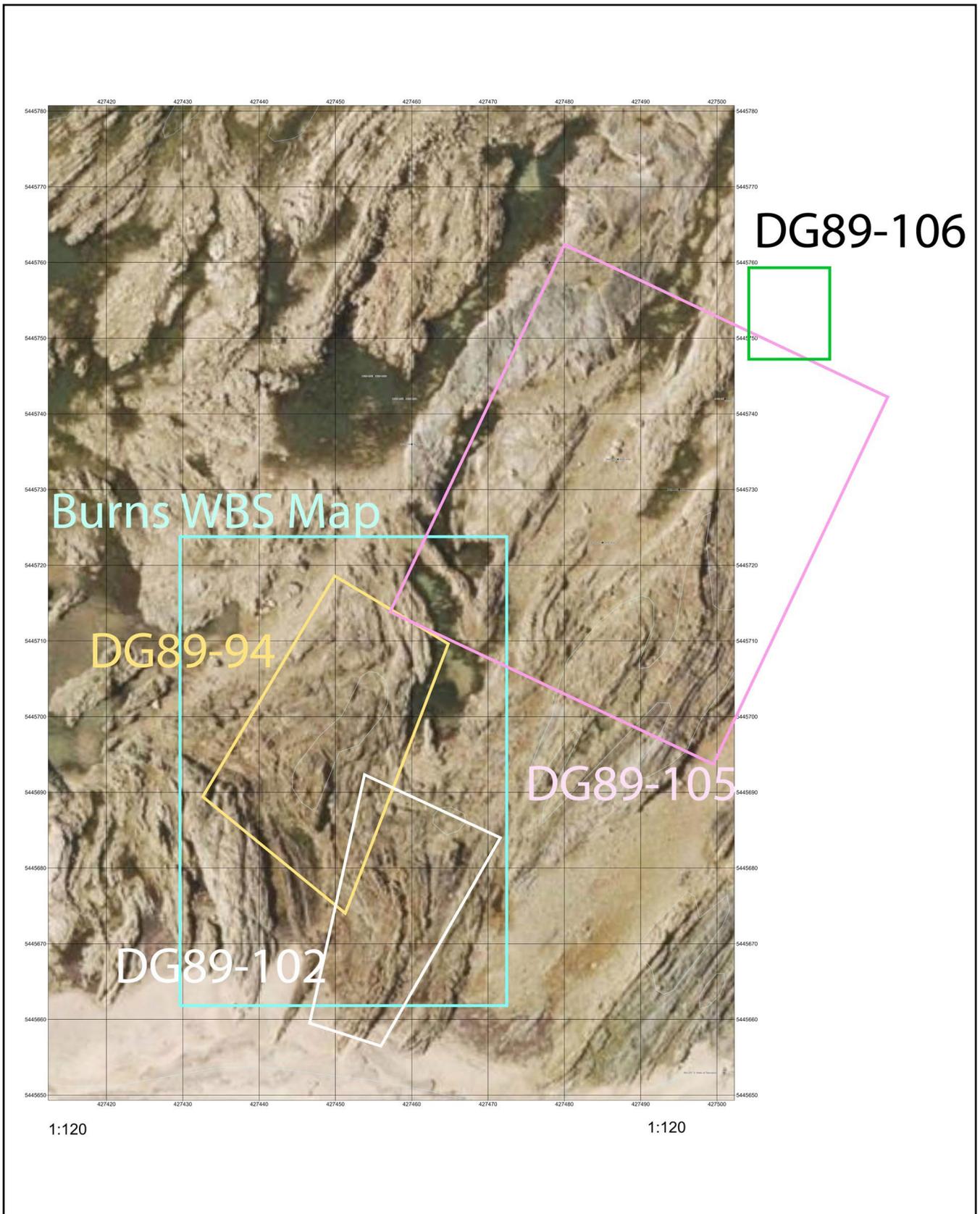


Figure 82. Locations of DG89 detailed structural sketch maps shown on a georeferenced ListMap™ Google satellite image. The Westbank Siding map of Burns (1964, fig. 40) is shown by the teal box outline. DG89-105 outline is Figure 84. DG89-94 is Figure 83.

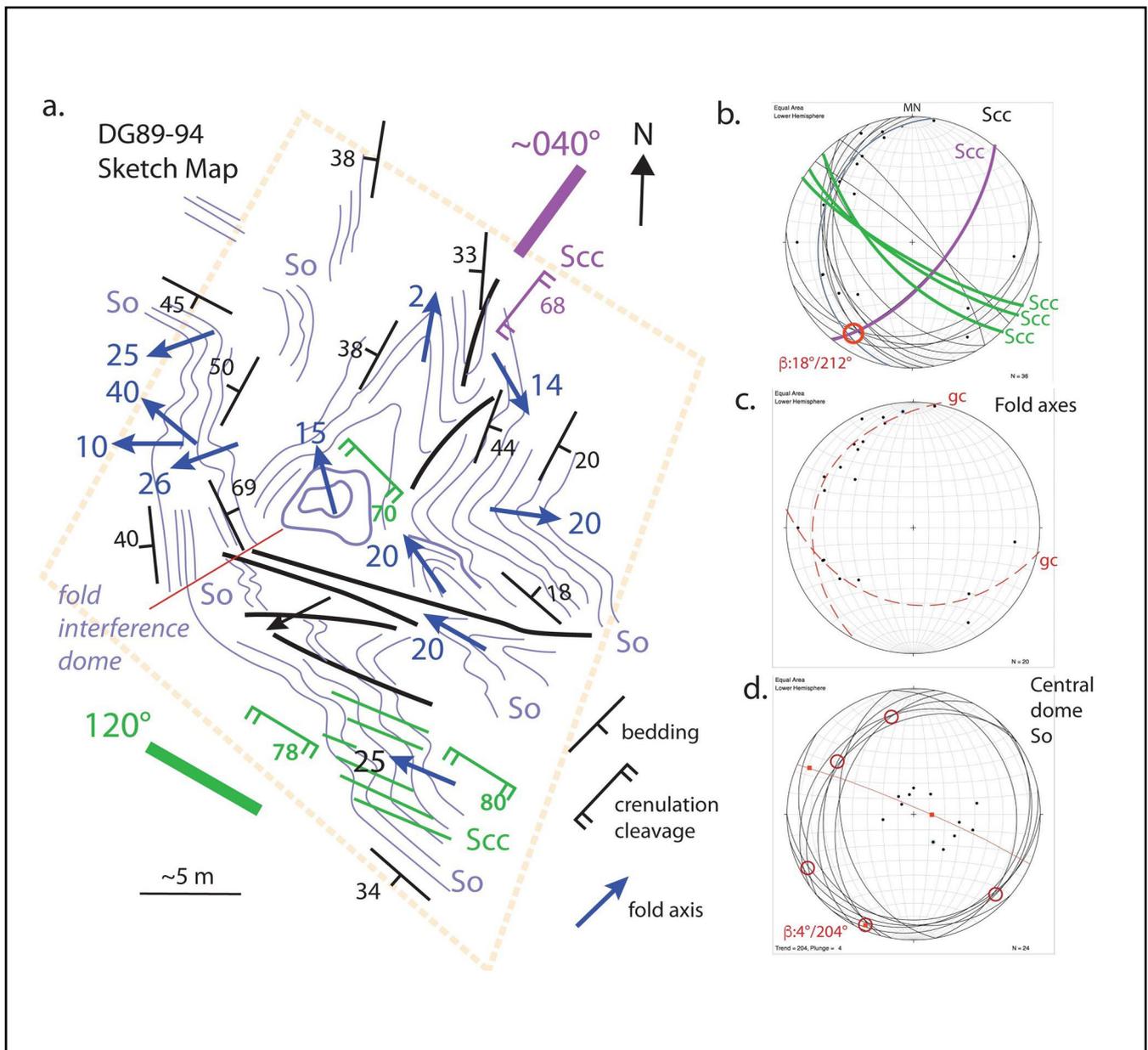


Figure 83. Structural sketch map of the southern part of the fault-bounded fold-interference domain within the Oonah Sheet as hanging wall to the Singleton Fault (see Figures 81 and 82 for location). a) Structural form line map with bedding form lines (blue line traces), faults (heavy black line traces) and crenulation cleavage (green line traces). b) Bedding great circle traces giving a b intersection of  $18^{\circ}/212^{\circ}$  (magnetic) and crenulation cleavage great circle traces (NE-trending: purple great circle and NW-trending: green great circle traces). b) Fold axis attitudes showing spreads along two great circles (red dashed great circle traces). d) Bedding attitudes (great circles) around the centrally located fold interference dome due to interference between the NW- and NE-trending fold sets/ crenulation cleavages. Multiple intersection points (red circles) suggest an apparent radial fold axis distribution across the central dome.

#### 4.1.2 Footwall Structural Relationships (Ulverstone Sheet slice)

The Ulverstone Sheet at Goat Island is a fault-bounded slice in the footwall of the Singleton Fault trapped between this fault and the Westbank Fault with a map width of  $\sim 540$  m (Figure 85). Burns (1963a, 1964) showed the footwall, although predominantly pebble conglomerate, had structurally intercalated pelite layers that were folded at 100-metre scale in the immediate footwall ramp (Figures 77, 86 and 87). See Appendix C for more photos.

##### 4.1.2.1 The Goat Island Conglomerate

The deformed pebble conglomerate exposed at Goat Island (Figure 88) consists of elongated pebble- to boulder-size

quartzite bodies of various shapes within a sparse foliated phyllitic matrix (Figures 89 and 90). Dimensions of  $30 \times 15 \times 7$  cm are common (Spry and Burns, 1967). Pebble long axes are parallel to L2 and are generally sub-horizontal (Burns and Spry, 1969). Measurements of pebble axial ratios ( $l > m > n$ ; Figure 90) at Goat Island gives a modal ellipsoid shape of 2:1:0.5 and a Flinn k value of  $k=1$  (plane strain) (Burns, 1963a, 1964). Pebbles are boudinaged, segmented, nested and cut by shear bands (Spry and Burns, 1967). Much of the original lithology was probably conglomerate, similar to that exposed at Spalford approximately 16 km south of the coastal exposures (Burns 1964). However, there is evidence that some pebbles are pseudo-pebbles derived by boudinage and dismemberment of quartzite beds (Spry and Burns, 1967).

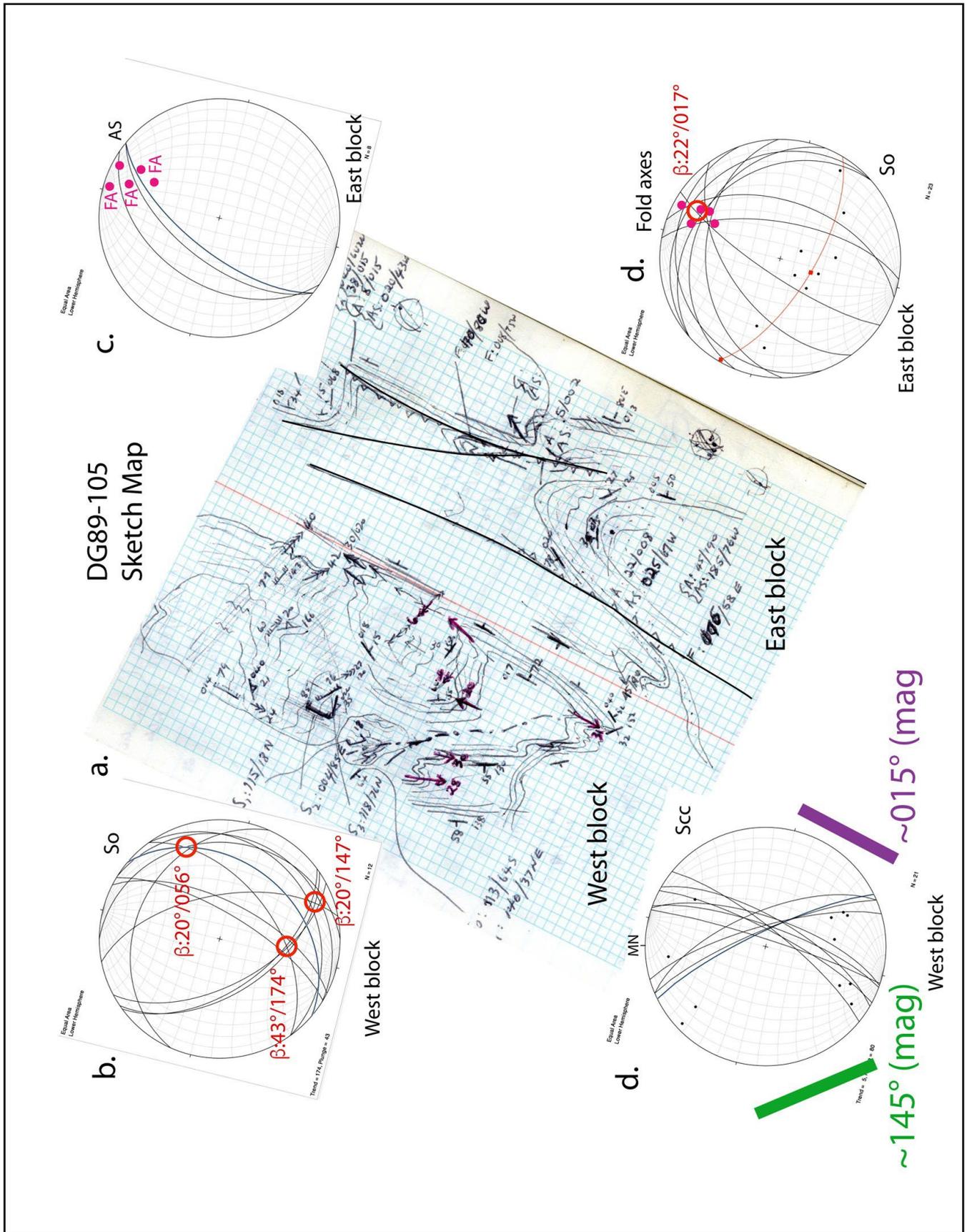


Figure 84. Structural sketch map of the fault-bounded folded domain (east block) and poly-deformed, fold interference domain within the hanging wall of the Singleton Fault (see Figures 81 and 82 for location). a) Sketch Map showing the central fault partition between West block and East block. b) Stereonet of bedding So great circle traces and  $\beta$  intersections (red circles= fold axes) for the dom,al core of the West block. d) Stereonet showing the two sets of crenulation cleavages within the West block. These are  $\sim 145^\circ$  and  $\sim 0015^\circ$ . c) Stereonet of fold axial surfaces and fold axes (red dots) within the East block. d) Bedding great circle traces , fold axes (red dots) and a  $\beta$  intersection of  $22^\circ/017^\circ$ . All stereonets have been rotated so that TN is at the top of the net.

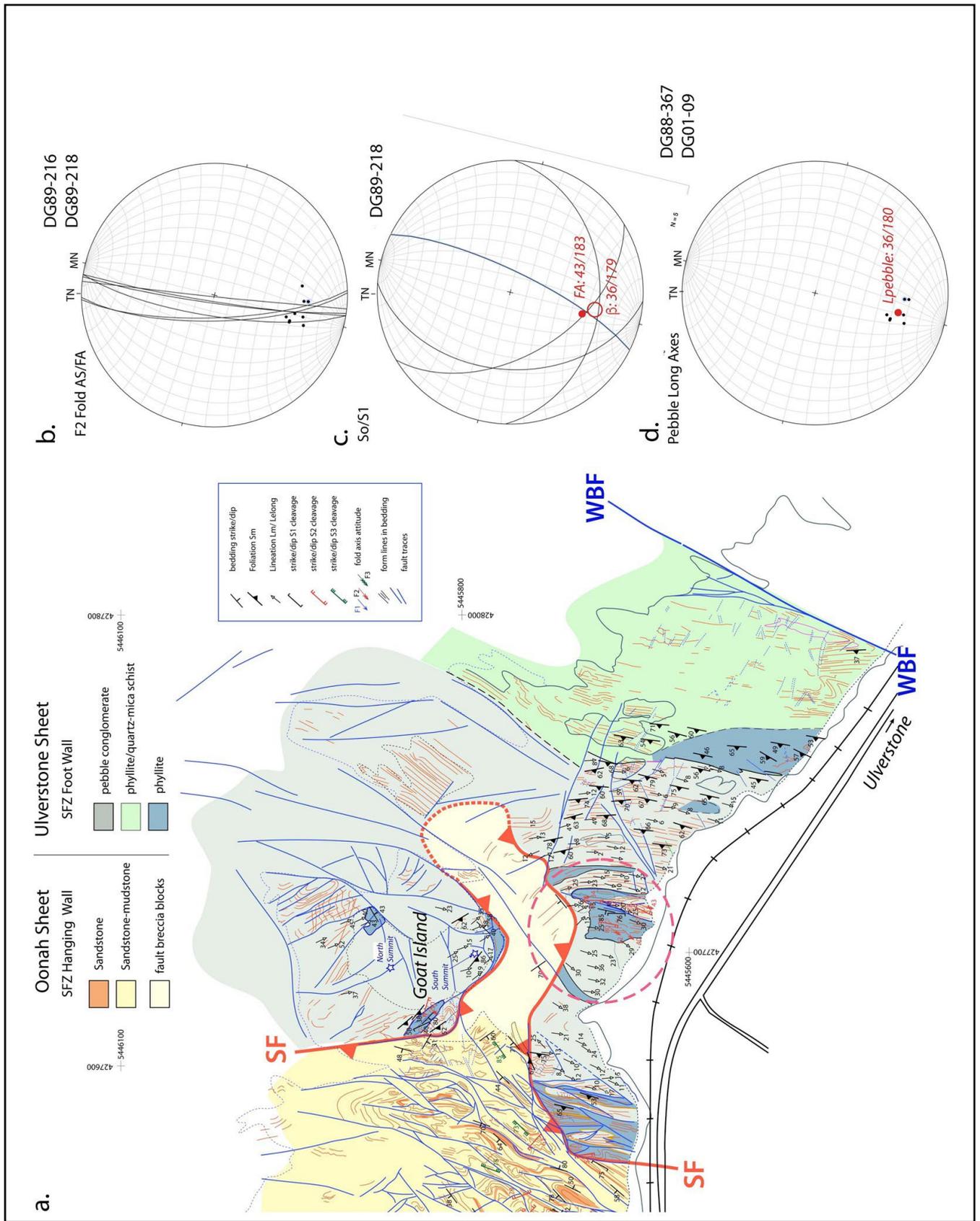


Figure 85. Structure of the Goat Island conglomerate. a) Structural map of the Goat Island slice of the Ulverstone Metamorphic Sheet. The slice is bounded by the Singleton (SF) and Westbank (WBF) Faults. Structural data plotted in the stereonets is from the area enclosed by the pink dashed circle. b) F2 fold axial surface great circle traces and fold axis data (black dots). c) Bedding (So) great circle traces with measured fold axis and calculated  $\beta$  axis. d) Pebble long axis data. All synoptic measurements (red text) are magnetic.

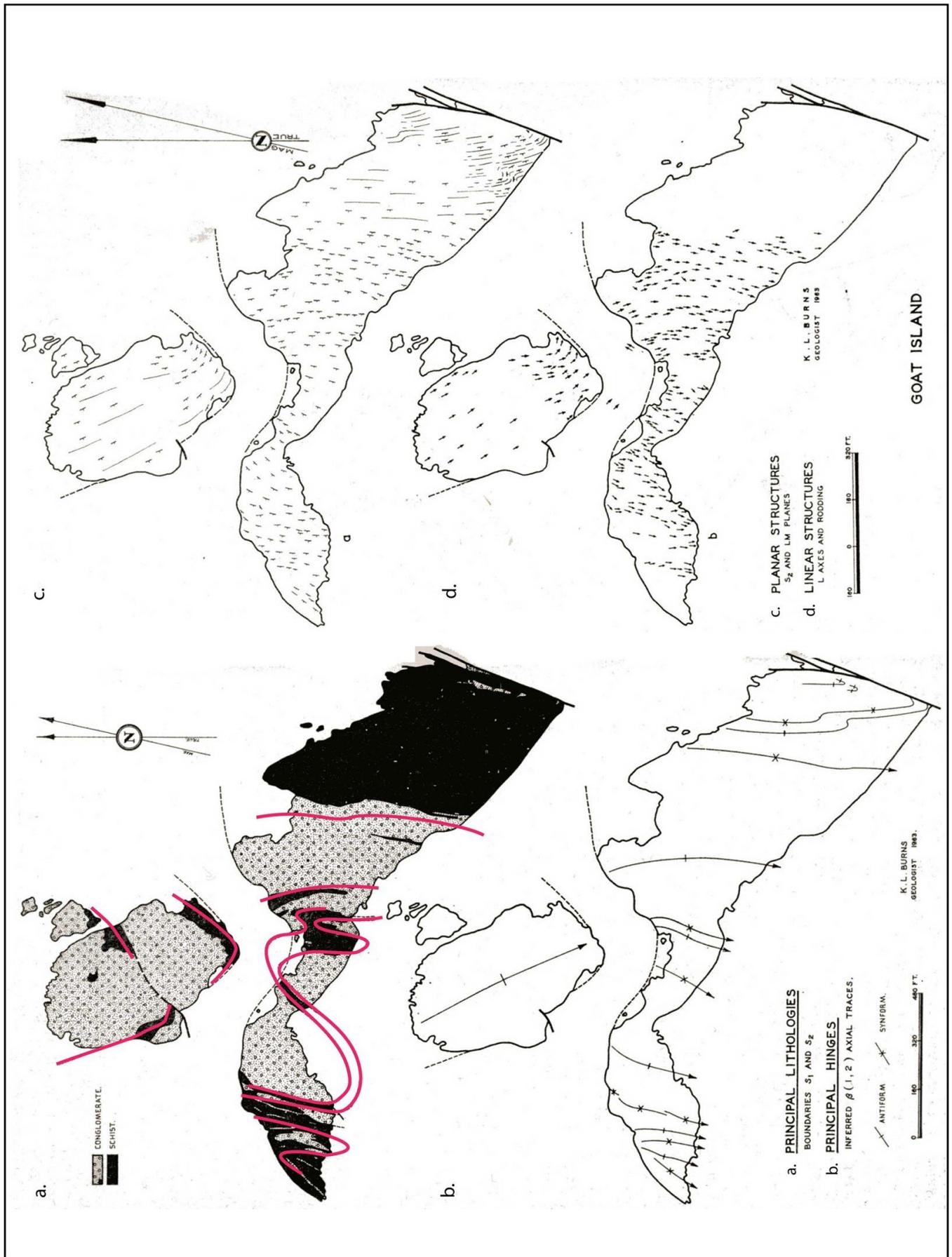


Figure 86. Goat Island structural maps from Burns (1964, figs. 31 and 32). a) Lithology map. Black: schist. Dots: pebble conglomerate. b) Fold axial surface trace map. c) Foliation strike trace map. d) Lination trend map.

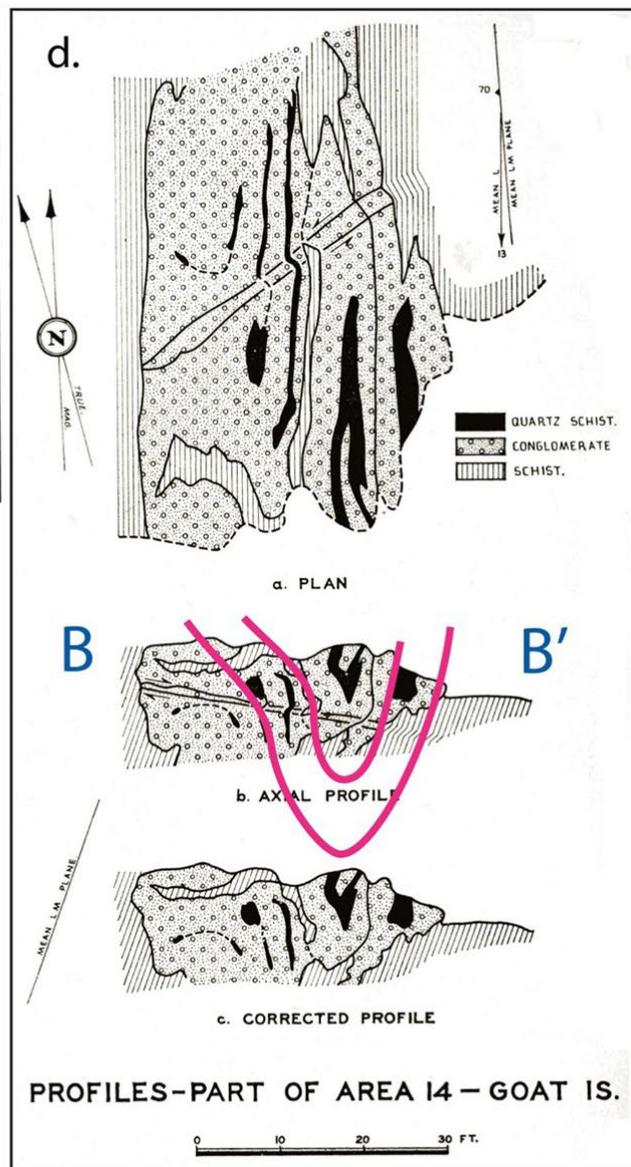
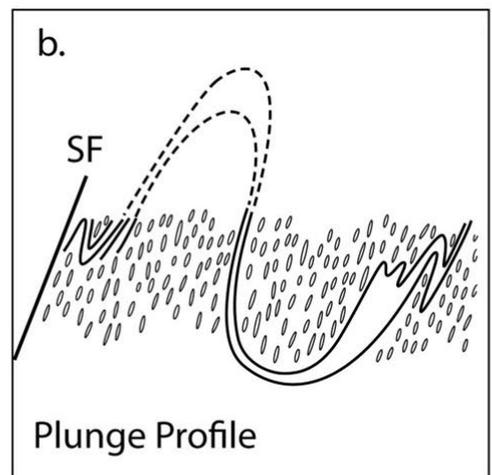
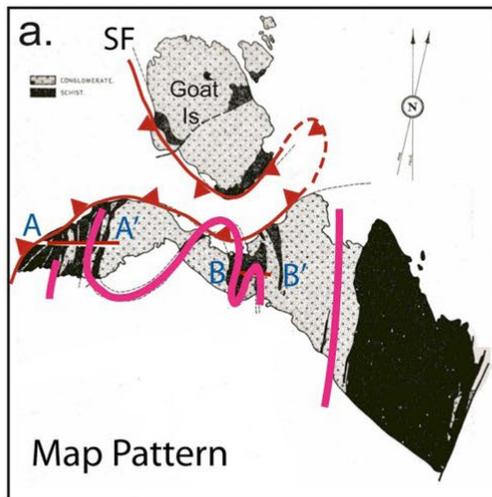
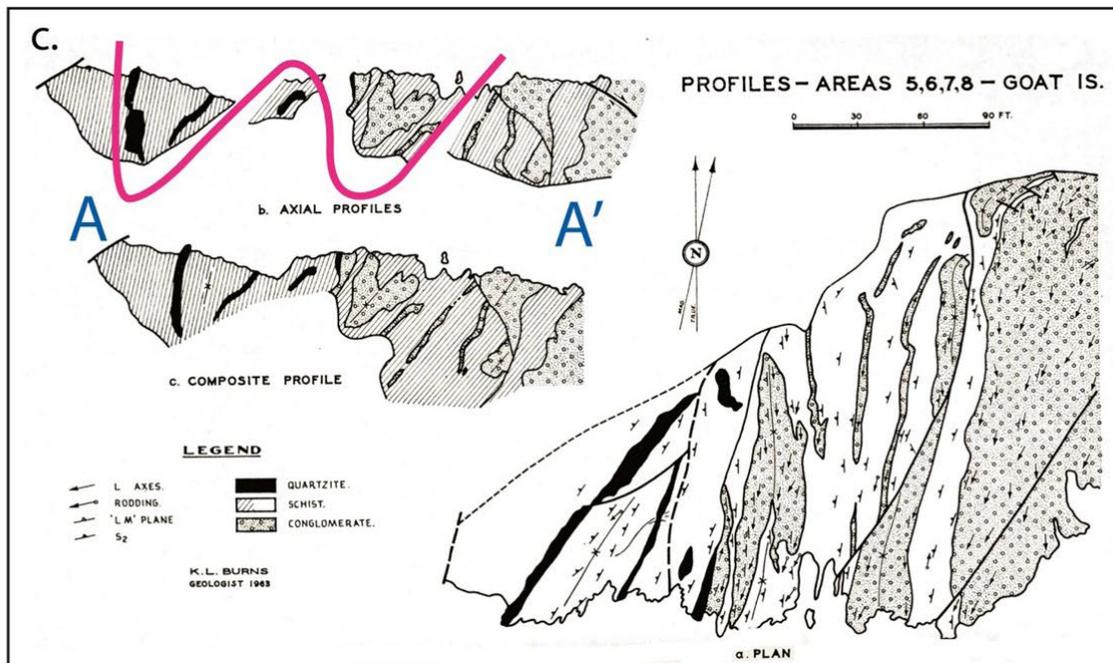


Figure 87. Burns (1964) profiles across part the southern part of the Goat Island conglomerate. a) Map showing the locations of the profiles A-A' and B-B', the barbed outcrop trace of the Singleton Fault and form lines in the lithological contacts. b) Generalised profile across the southern part of the Goat Island conglomerate. c) Map and profile of A-A' area (Burns, 1964, fig. 33). d) Map and profile of B-B' area (Burns, 1964, fig. 34).

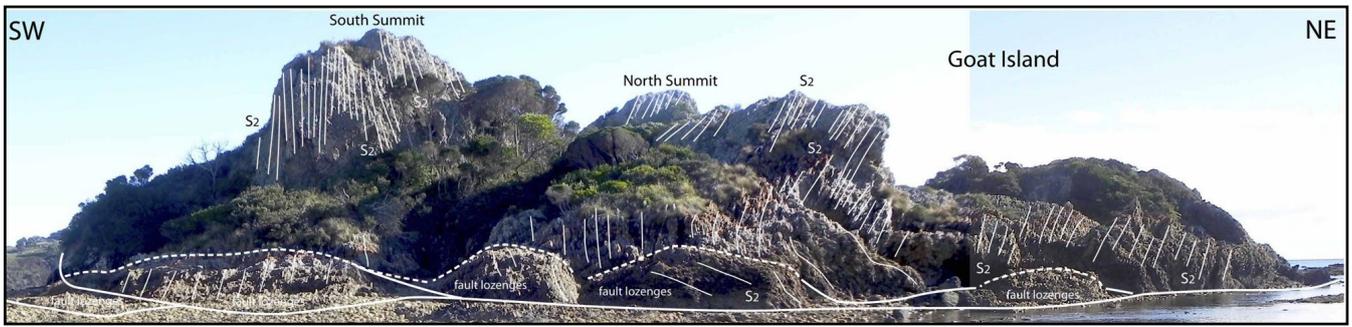


Figure 88. Photo profile of Goat Island with structural interpretation. The view is to the northwest. The intersection trace of the steeply dipping to sub-vertical Singleton Fault and splays are shown by the thick white line and dashed lines along the base of the island. Dashed thick lines represent splay faults that are hidden behind the blocks of pebble conglomerate designated as fault lozenges. The dominant foliation in the pebble conglomerate is S2.

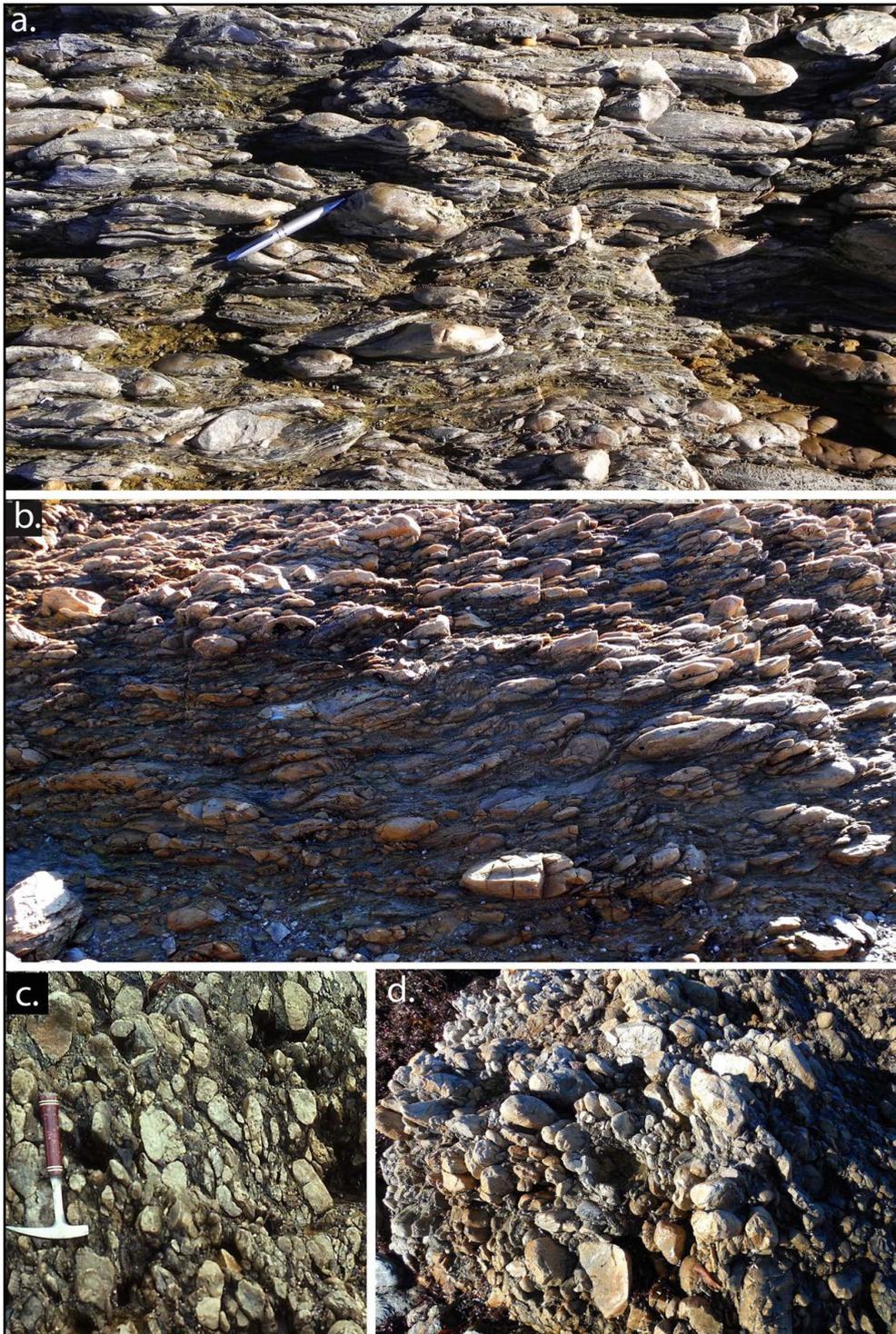


Figure 89 (Left). Sectional views of the Goat Island deformed pebble conglomerate. a) Plan view of outcrop (XZ section). b) Side view of outcrop (XY section). c) and d) End view of outcrop (YZ section). X: pebble long dimension. Y: pebble intermediate length dimension. Z: pebble short dimension. Where  $X > Y > Z$ .



Figure 90. Goat Island deformed pebble tecton (after Burns 1964). a) Typical quartzite pebble. b) Pebble shape dimensions after Burns (1964).

#### 4.1.2.2 The Intercalated Pelite

Infolds and/or closures of interbedded pelite occur within the pebble conglomerate that dominates the Ulverstone Metamorphic Sheet at Goat Island (Figures 86 and 87). These folds are F2 folds (Burns, 1963a, 1964) as shown by refolding and overprinting cleavages (Figures 91 and

92). The early folding event is preserved by coaxially re-folded, F1 fold hinges within syn-D1 folded quartz gash veins (Figures 91c and d). The veins and layering predominantly show upright, south plunging F2 fold hinges with a strong, axial surface S2 crenulation cleavage fabric (Figures 91, 92 and 93). The interpreted deformation chronology is shown in Figure 91 (figure right).

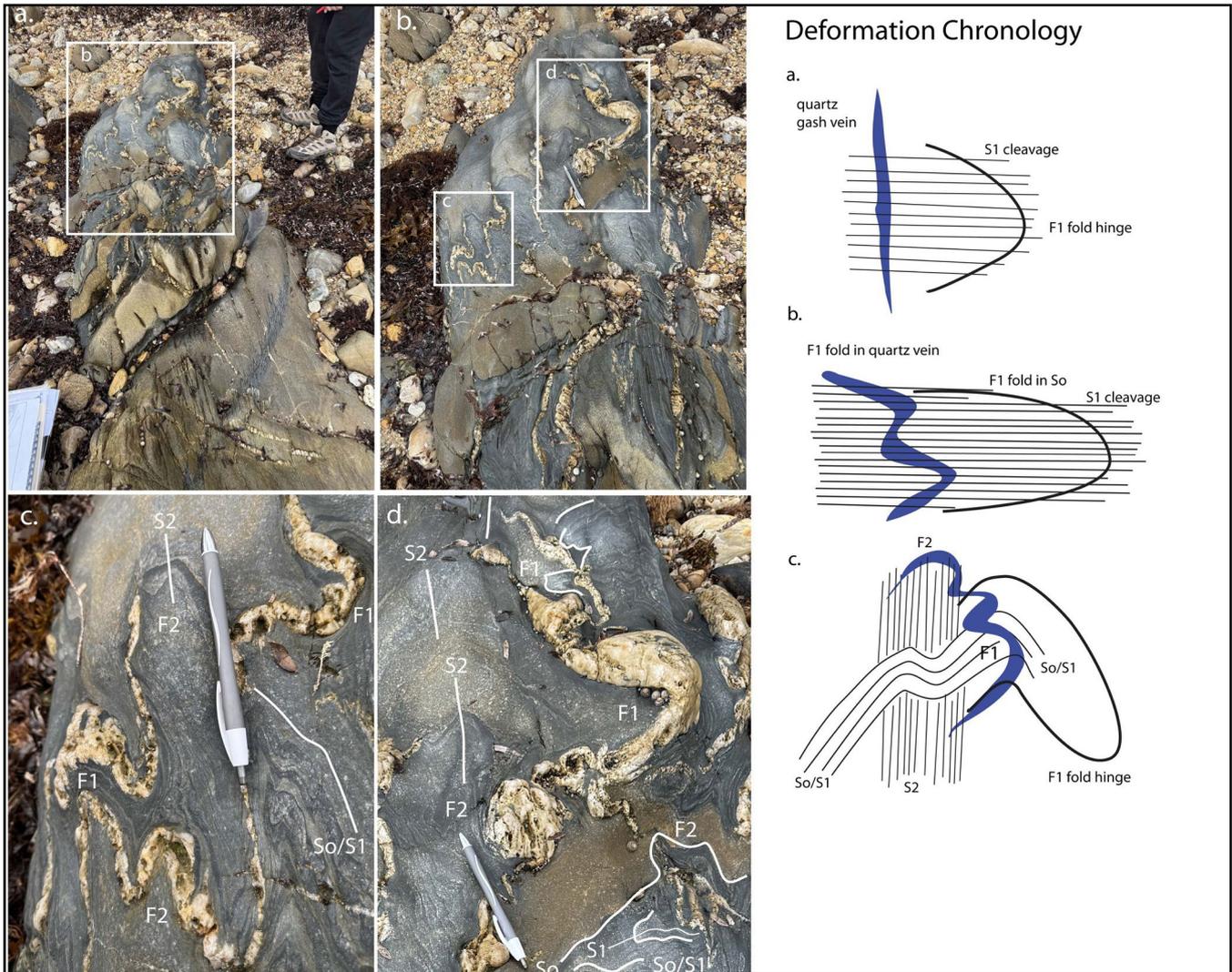


Figure 91. Deformation chronology of the Ulverstone Metamorphic Sheet based on overprinting and refolding relationships within pelite that is infolded within the deformed pebble conglomerate. a), b) c) and d) are outcrop photographs (Station DG89-218/DG01-9) showing south-plunging (to top of photo), coaxially refolded bedding and quartz veins in a cleaved, largely mudstone-siltstone unit. The dominant foliation is a sub-vertical S2 crenulation cleavage that is axial surface to the mostly F2 folds within the outcrop. c), d) are enlargements of parts of the outcrop. Field sketches a), b) and c) show a schematic evolution of the structural relationships in the field photographs.

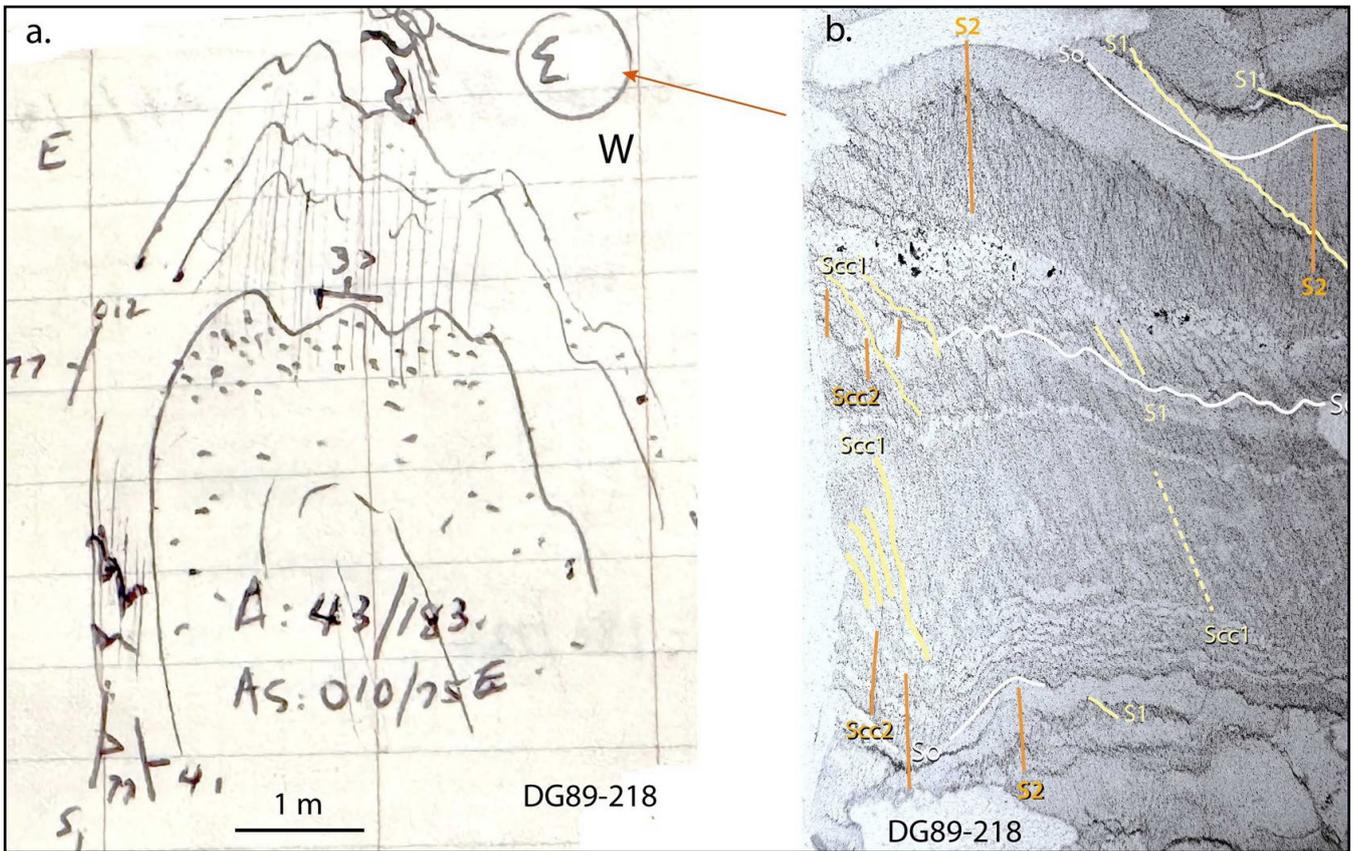


Figure 92. Overprinting cleavages within the hinge zone of a south-plunging, upright, antiformal fold within a pelite layer that is intercalated with the Goat Island deformed pebble conglomerate (Station DG89-218). a) Field sketch of the antiformal fold. b) Photograph of thin section sampled top right ( $\Sigma$ ) in (a). Two overprinting crenulation cleavages Scc1 (yellow line traces) and Scc2 (orange line traces) locally interfere and overprint with Scc2 axial surface to the macro-fold sketched in (a). The pelitic layers are dominated by partially recrystallised detrital mica such that the first cleavage has spaced crenulation cleavage morphology (compare with Figure 93).

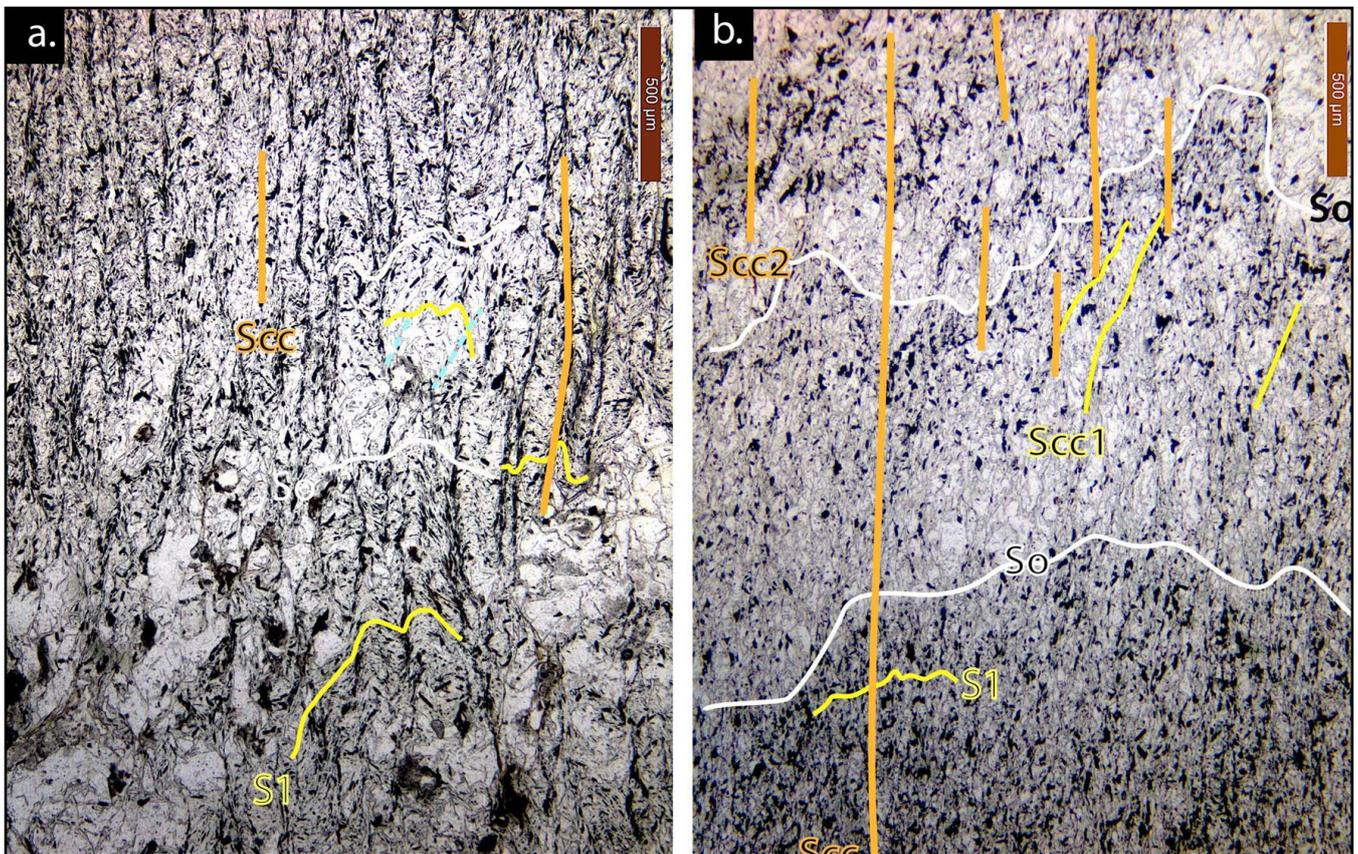


Figure 93. Photomicrographs of the spaced, Scc2 crenulation cleavage fabric in pelite layer dominated by partially recrystallised detrital mica. The pelite layer is intercalated with the Goat Island pebble conglomerate (Station DG89-219). a) Spaced crenulation cleavage fabric within a detrital mica So/S1 bedding parallel fabric. The early S1 fabric is at low angles to bedding (So) but is mostly sub-parallel to bedding defined by siltstone layers So. b) is an enlargement of part of the siltstone layer showing suggestion of the presence of a weak Scc1 fabric.

In thin section the fabrics of the schist-phyllites are low metamorphic grade with a strong presence of detrital micas (Figures 92 and 93). Overprinting crenulation cleavages Scc1 and Scc2 reflect this detrital mica component (Figures 93a and 93b) with the first cleavage showing either a primary slaty fabric transitioning into a primary crenulation cleavage in layers dominated by detrital mica.

#### 4.2 West Ulverstone Slice (Fault Slice 2)

The West Ulverstone slice (Fault Slice 2) is part of a composite, fault-bounded, slice made up of sub-greenschist facies Oonah Formation mudstone-sandstone "welded" to part of the Ulverstone Metamorphic Sheet (Figure 73). This composite slice sits in the hanging wall of the Ulverstone Fault Zone and extends from the Westbank Fault Zone to the Ulverstone Fault Zone (Figures 73 and 74).

##### 4.2.1 Structure of the West Ulverstone Oonah L-G Slice

The West Ulverstone Oonah L-G slice is exposed in the coastal wave cut platform from the Westbank Fault Zone eastwards to the contact with the Ulverstone Metamor-

phic Sheet (Figures 94 and 95). It is a mudstone dominant, mudstone-sandstone sequence with foliated pelite (mudstone) entraining both elongated, tabular bodies of sandstone (<5 m thick) and irregular shaped pods of sandstone representing former channels (Figures 96 and 97).

Isolated, irregular shaped sandstone bodies occur in 100-150 m wide zones and are separated by smaller zones (<50 m) of tabular, more continuous sandstone (Figures 96 and 97). The irregular shaped sandstone bodies are end-on-views or sections through now steeply dipping, sandstones occupying former channels (Figures 98, 99, 100, 101 and 102), whereas the tabular more continuous sandstone layers are sediment sheets as overbank deposits away from the channels (see Figure 103a).

The structural form lines trend ~040°-045° and are discordant to the ~033° trending Westbank Fault Zone on the west (Figure 96). The eastern boundary trends ~025° and is an Sm foliation-parallel contact with the Ulverstone L-G Slice (quartzite/pebble conglomerate sequence) on the east (Figures 94 and 96).

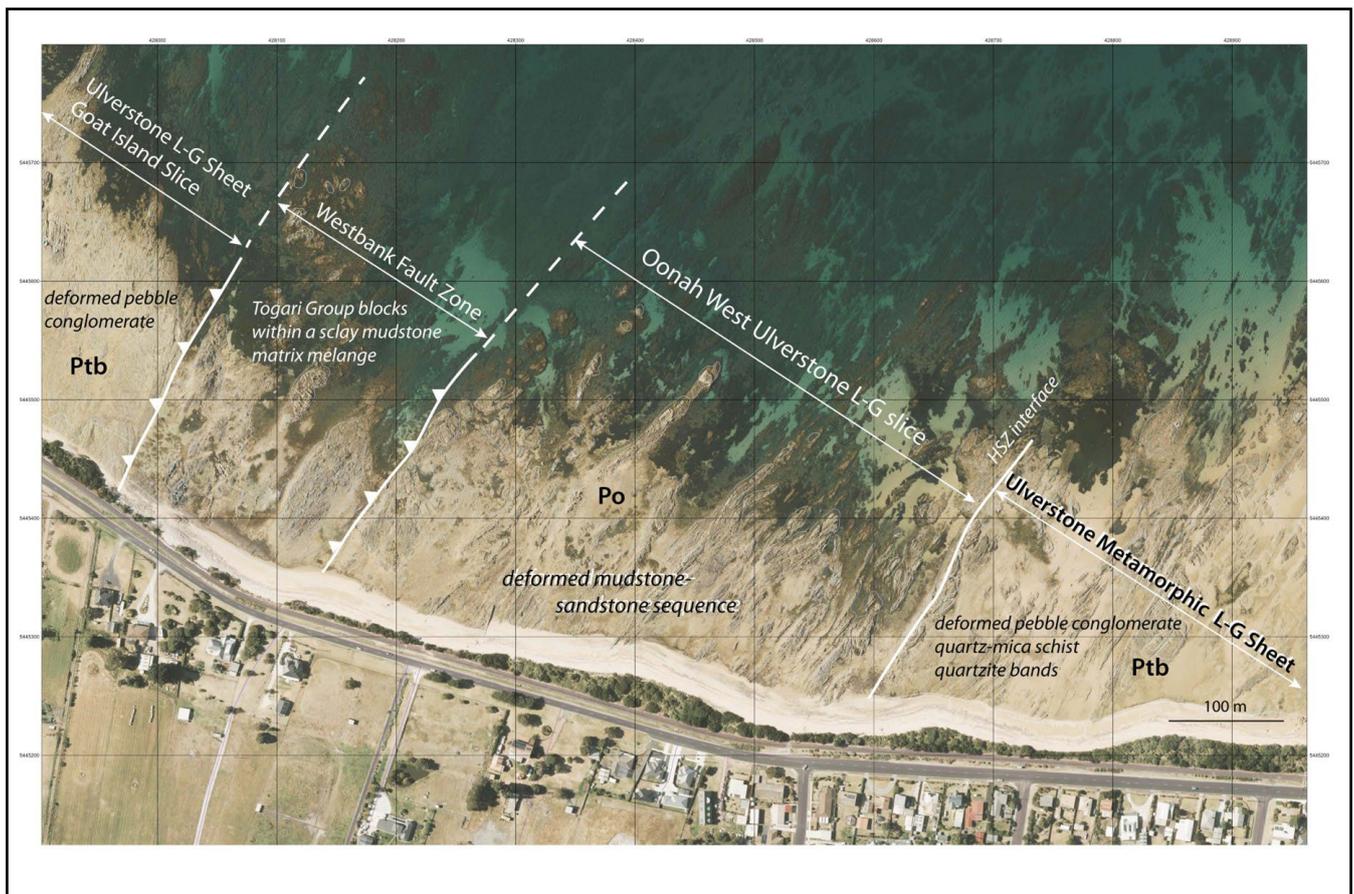


Figure 94. Georeferenced Google satellite image showing the major structural-tectonic elements of the West Ulverstone beach low tide exposures. The West Ulverstone Oonah L-G slice (image centre) sits east of, and in the footwall to the Westbank Fault Zone. The Oonah slice is part of a composite, fault-bounded, slice made up of sub-greenschist facies Oonah correlate mudstone-sandstone "welded" to part of the Ulverstone Metamorphic Sheet. This composite slice sits in the hanging wall of the Ulverstone Fault Zone (Figure 74).



Figure 95. Structural So form line map of the West Ulverstone Oonah L-G slice. The western contact is the Westbank Fault Zone and the eastern contact is a foliation parallel HSZ. The map base is a georeferenced Google Satellite image.

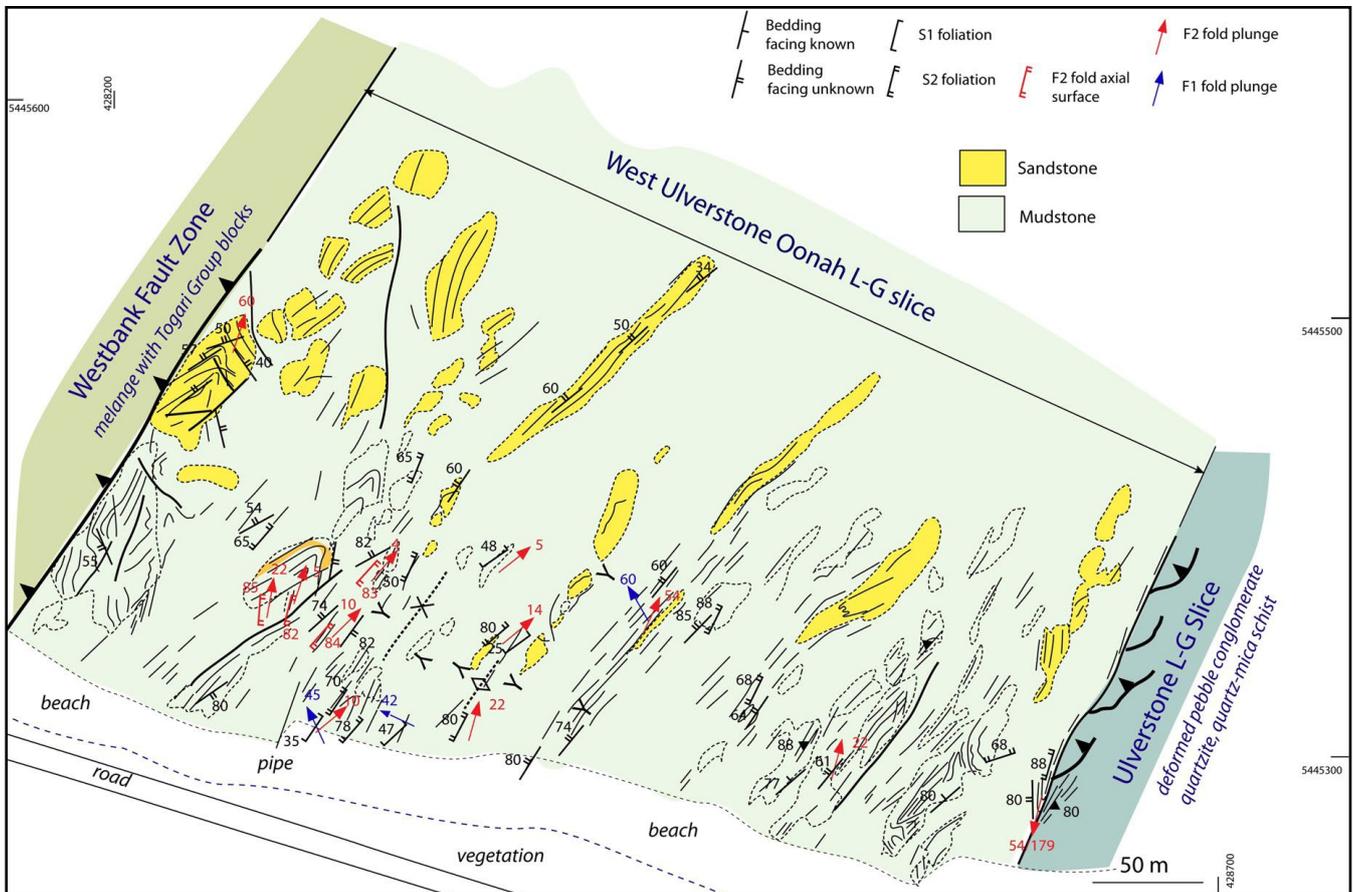


Figure 96. Structural map of the West Ulverstone Oonah L-G slice. Areas of outcrop are shown by the closed stippled lines. The bedding and foliation (S2) form lines are shown by the fine black lines. The structural form lines trend  $\sim 040^{\circ}$ - $045^{\circ}$  and are discordant to the  $\sim 033^{\circ}$  trending Westbank Fault Zone on the west. The eastern boundary trends  $\sim 025^{\circ}$  and is an S<sub>m</sub> foliation-parallel contact with the Ulverstone L-G Slice (quartzite/pebble conglomerate sequence) on the east.

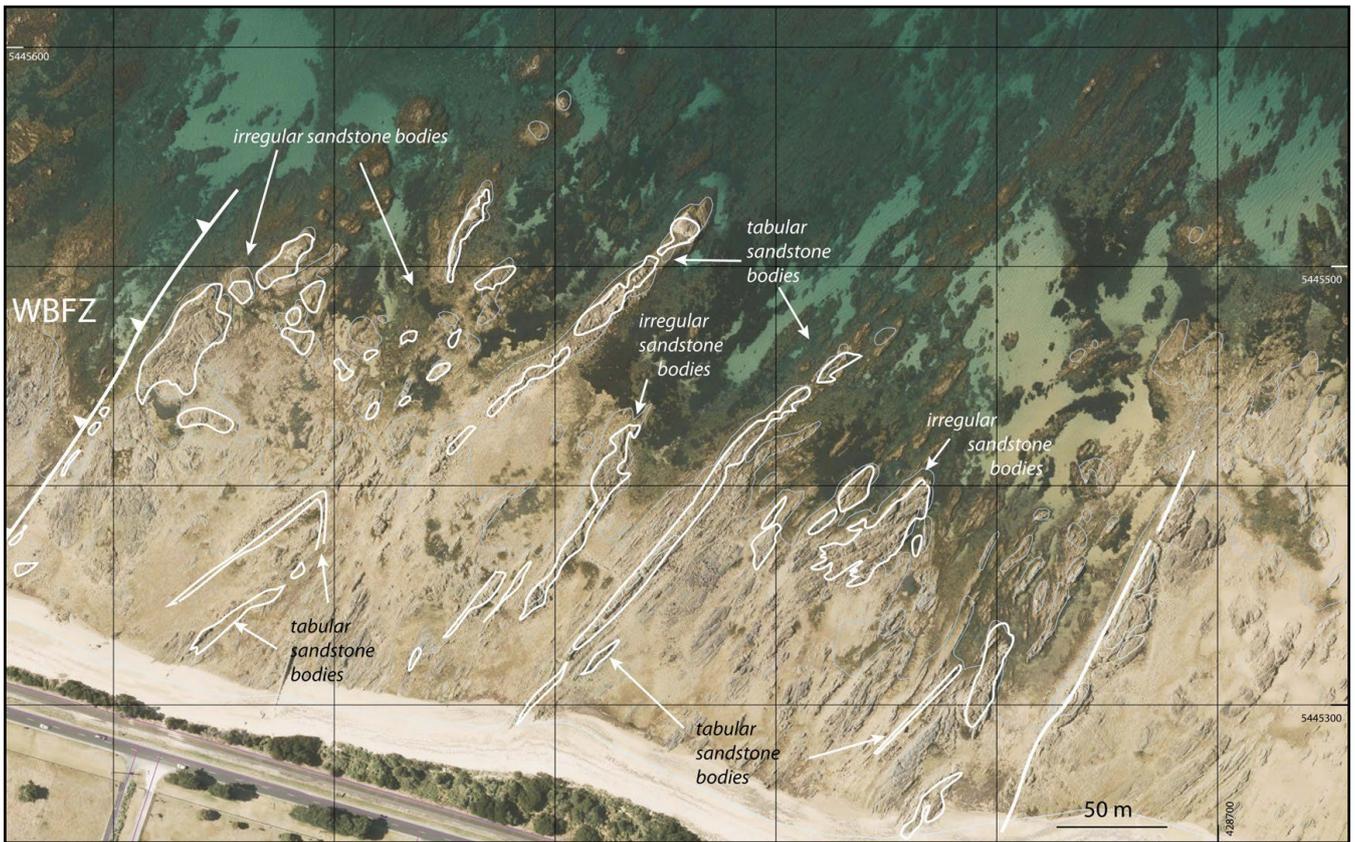


Figure 97. Oonah Formation lithological outcrop map. The white outlines highlight isolated sandstone pods and layers. The map shows alternating 100-150 m wide zones of isolated, irregular shaped sandstone bodies separated by tabular, more continuous sandstone. The irregular shaped sandstone bodies are end-on-views or sections through now steeply dipping, sandstones occupying the former channels, whereas the tabular more continuous sandstone layers are sediment sheets as overbank deposits away from the channels (see Figure 103a).

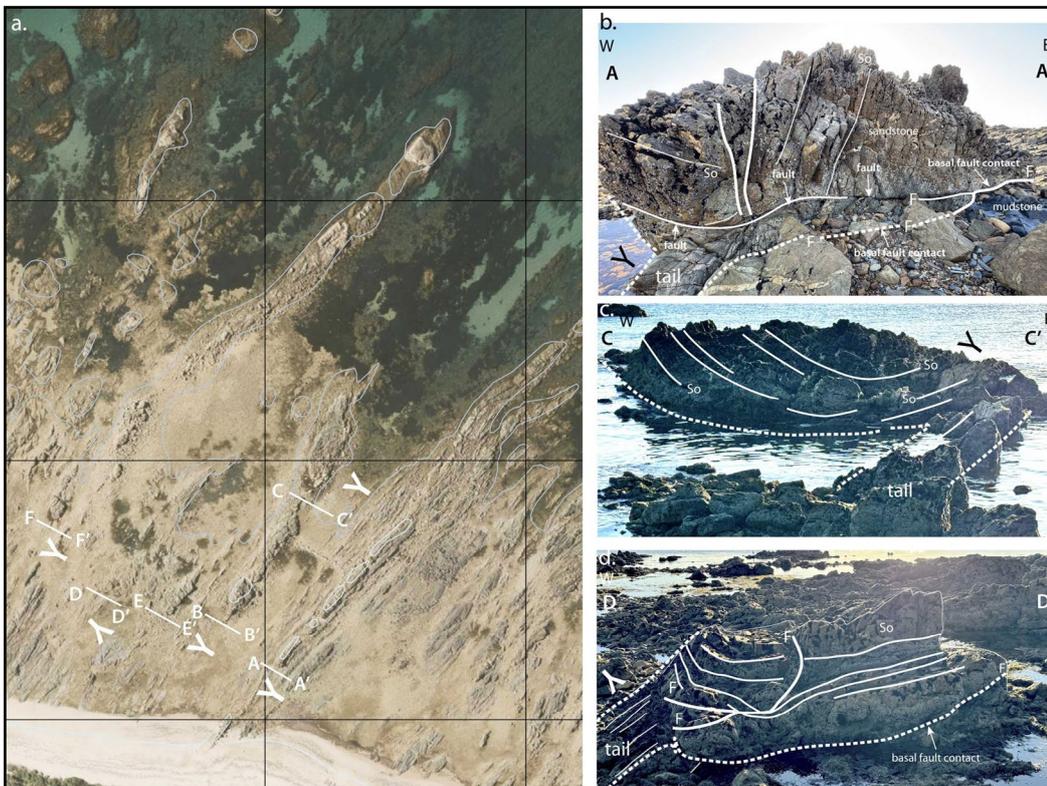


Figure 98. Sectional, across-strike views of the now, steeply dipping, channel sandstone bodies and layers. a) Georeferenced Google satellite image (grid squares are 100 m x 100 m) showing the locations of the various photo profiles. b) Photo profile A-A' showing an irregular shaped, east facing sandstone body with "tail" (lower left). Note the fault truncation, without offset, near the top of the now inverted sandstone body. c) Photo profile C-C' showing a downwards, east-facing, sandstone channel body with a tabular sandstone layer as "tail" (photo right). Note some of the sandstone bodies show internal broad, open folds in bedding (c and d) and truncation by brittle faults (b and d).

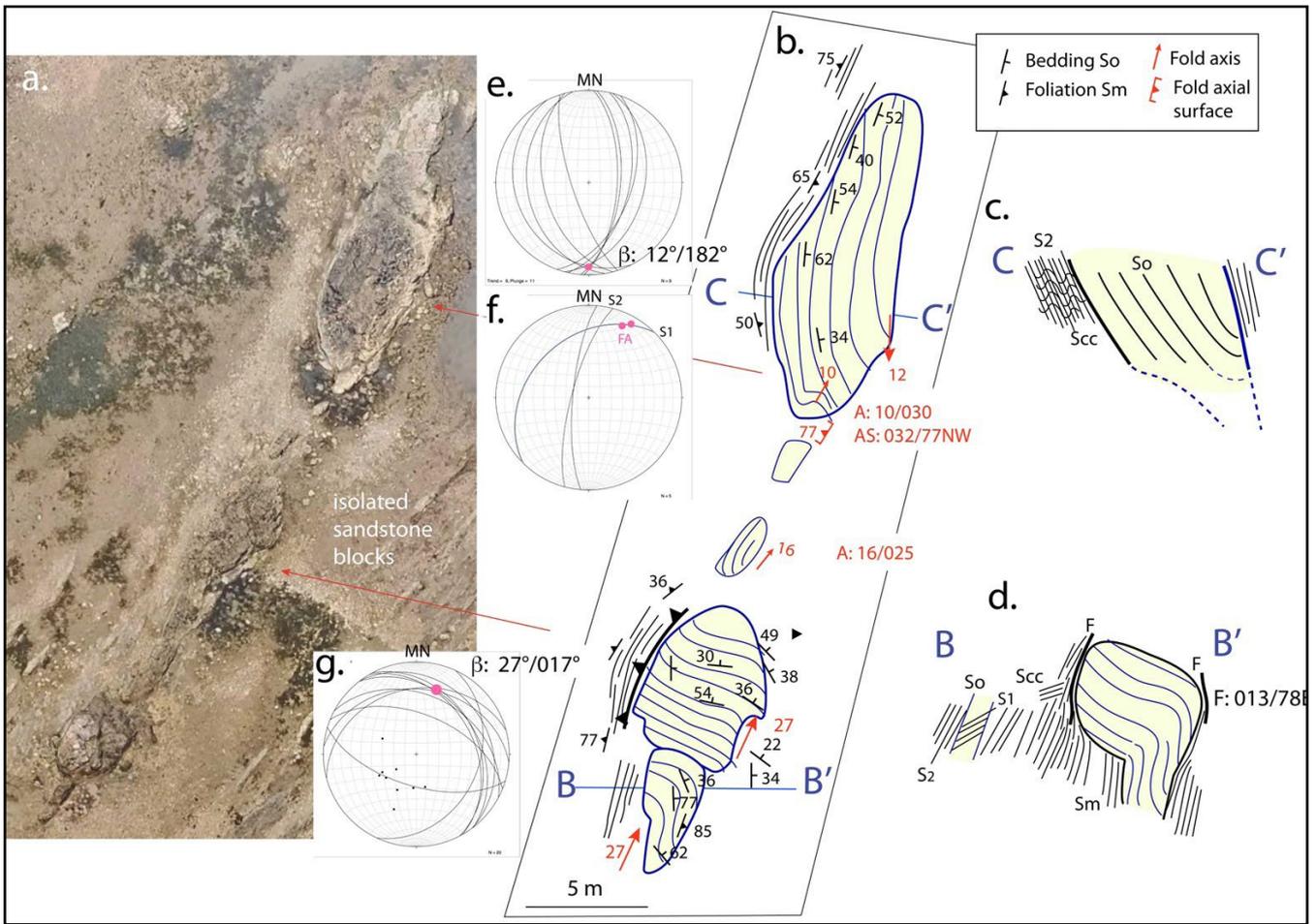
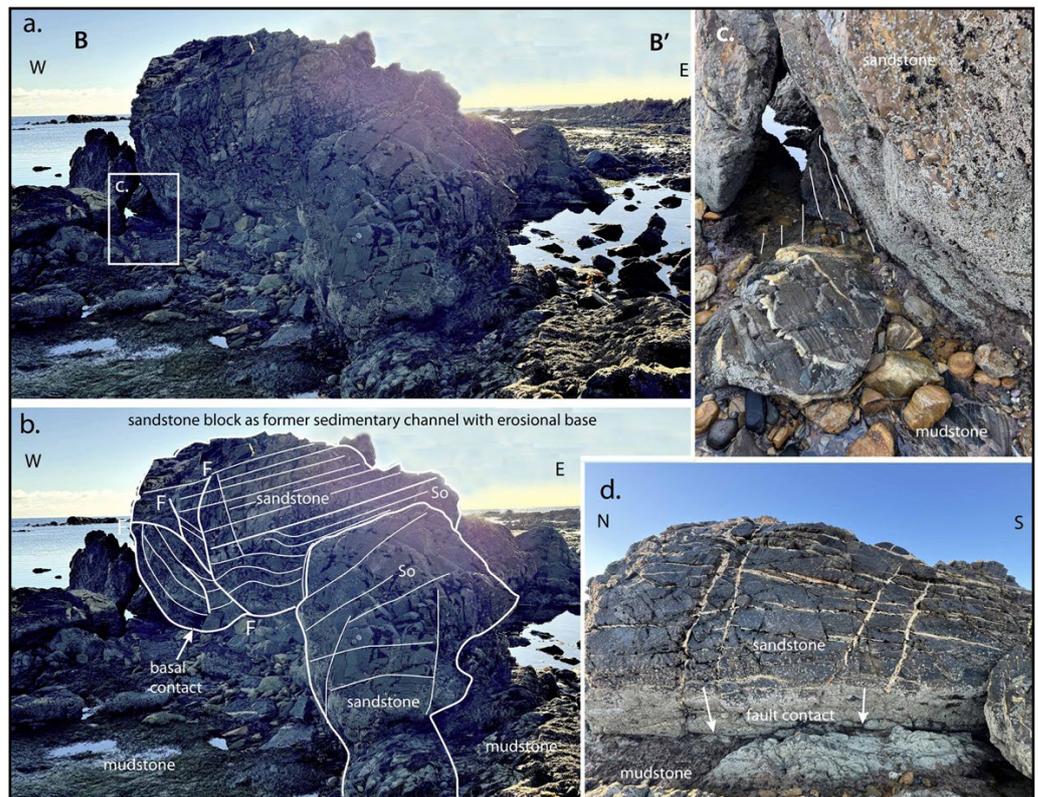


Figure 99. Apparent isolated sandstone channel-bodies within black mudstone of the Oonah Formation-correlate sandstone-mudstone sequence. a) Satellite image of a "train" of sandstone channel-bodies isolated within mudstone. b) Structural form line map of the "train" of sandstone channel-bodies shown in (a). Structural attitude data for bedding (So) and the dominant foliation in the mudstone are shown. c) Section C-C'. For location see map in (b). d) Section B-B'. For location see map in (b). Also compare with Figure 100 below. e) Bedding great circle traces with a fold axis  $\beta$  of  $12^\circ/182^\circ$  for the northernmost pod. f) Foliation S1 and S2 great circle traces from the mudstone matrix around the northernmost sandstone pod. g) Bedding attitude great circle traces from the southern sandstone pod with a fold axis  $\beta$  of  $27^\circ/017^\circ$ . See also Figure 98a for profile locations.

Figure 100. East-facing, irregular sandstone body showing a semi-continuous, steeply east-dipping, overbank sandstone layer (lower right) coming off the large, irregular, pod-like, channel sandstone (photo upper-middle). This is sandstone profile B-B' (see Figure 98a for location and Figure 99). a) and b) Non-annotated and annotated along strike view of the sandstone body. Note the apparent curved form of the basal contact. c) Basal contact of the channel sandstone body showing contact with black mudstone. White line traces define the foliation in the mudstone. d) Strike-normal view of the west side (i.e. base) of the channel sandstone body, given the steep east dip. The base has been reactivated as a brittle fault and the sandstone shows two approximately orthogonal quartz vein sets.



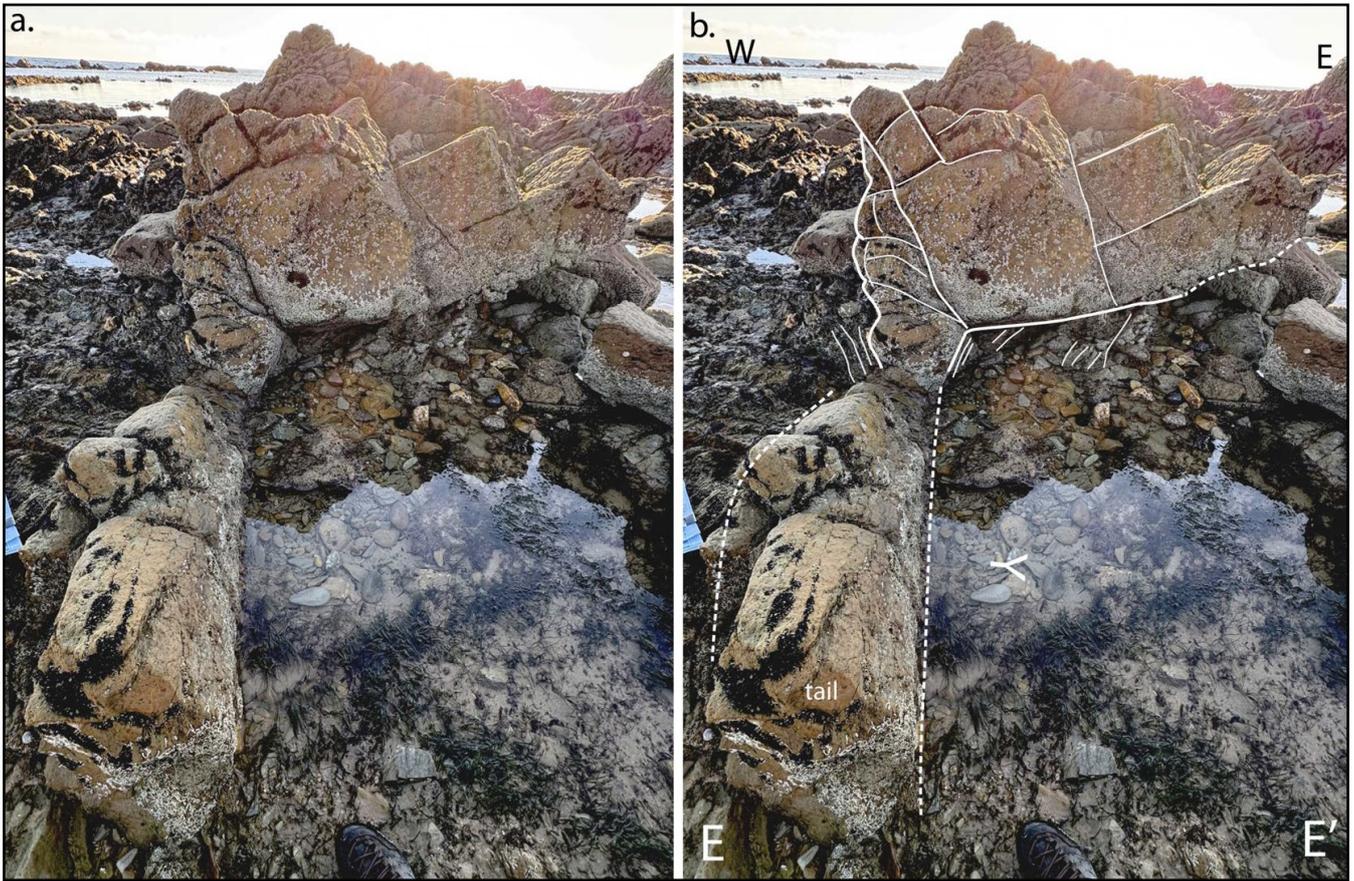


Figure 101. West-facing, steeply west-dipping, irregular sandstone body showing a thin, continuous, overbank sandstone (lower left) coming off the large, irregular channel sandstone (mid-upper right). This is sandstone profile E-E' (see Figure 98a for location).

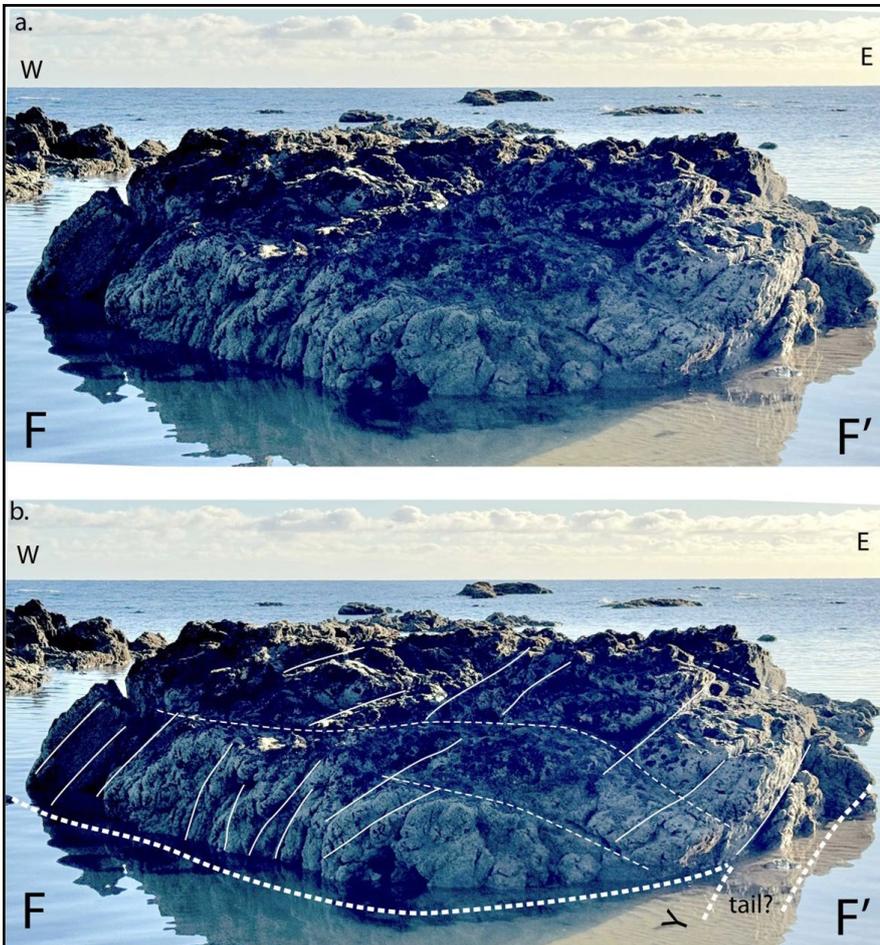
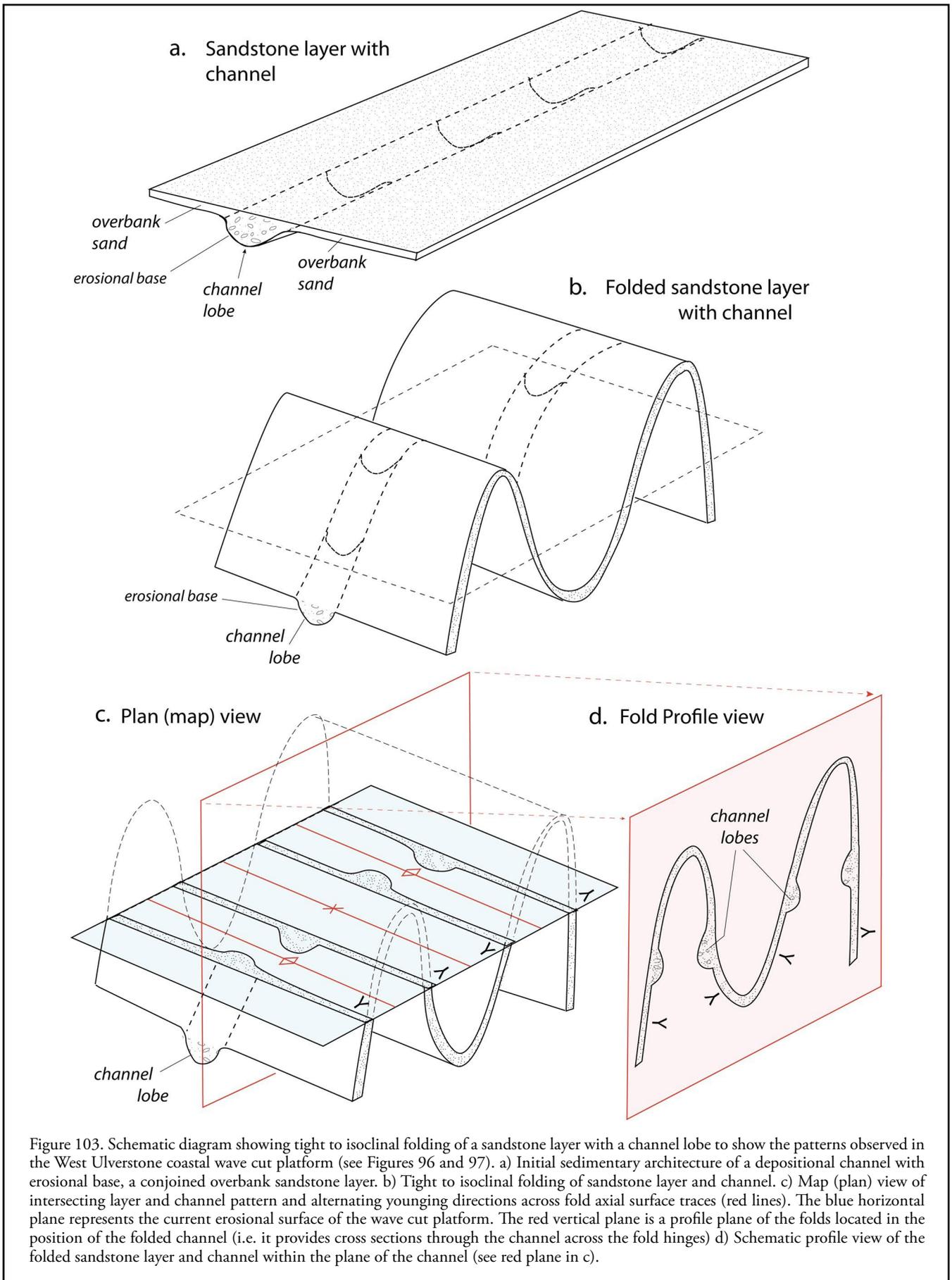


Figure 102. West-facing, irregular sandstone body showing a thin, continuous, overbank sandstone (lower left) coming off the large, irregular channel sandstone (mid-upper right). This is sandstone profile F-F' (see Figure 98a for location).



The mudstone is variably foliated from weak, where bedding lamination is clearly visible and at high angles ( $>30^\circ$ ) to the foliation, to strongly to intensely foliated, where the dominant sub-vertical foliation is sub-parallel to the bedding lamination.

In strong to intense zones the foliation envelopes the sandstone blocks. These blocks are also commonly bounded by faults that locally truncate the internal structure of the blocks that consists of warps or open folds in bedding (Figures 98 and 99).

Structurally the sequence has northeast strike and is generally steeply west dipping, with a strongly developed, steeply dipping foliation (Scc), commonly at low angles to bedding (Figures 104, 105 and 106). This dominant foliation is associated with upright, close to tight, gently to moderately plunging folds (red fold plunge arrows, Figures 104 and 105f). The foliation is considered S2 with crenulation cleavage (Scc) character, overprinting an earlier northwest dipping foliation, considered S1. The early foliation is preserved within some of the sandstone layers (Figure 110) and associated with apparent relicts of early, recumbent isoclinal folds (Figure 106). The early folds have northwest dipping axial surfaces with moderate west to northwest fold plunges (blue fold plunge arrows, Figure 96).

The upright folds (Figure 107) are most prominent in zones adjacent to the Westbank Fault Zone and the eastern pebble conglomerate-quartzite contact (Figure 106). These folds tend to have disharmonic form with faults separating fold packages that are part of the same folding event (Figure 108). A second crenulation cleavage (Scc)

overprints the dominant S2 foliation in places through the fault slice (Figure 96).

Stereonet of structural data from the West Ulverstone fault slice (Figure 105) show:

1. Bedding (So) has a northeast strike with variable dips either to the northwest or southeast (Figure 105b).
2. Great circle  $\beta$  intersections indicate that folds in bedding (So) have either gentle northeast or southwest plunges (Figure 105b).
3. The early foliation S1 has a consistent strike with moderate northwest dip (Figure 105c). The associated F1 mesoscopic folds have northwest plunges of  $\sim 40^\circ$  to  $60^\circ$  (blue fold plunge arrows, Figure 104).
4. The dominant foliation S2 is northeast striking with two apparent strike groupings with north-northeast strike and northeast strike (Figure 105d). These foliation S2 subsets are matched by a similar grouping in F2 fold axial surfaces (Figure 105f).
5. Faults have three groupings (Figures 105e and 113f).

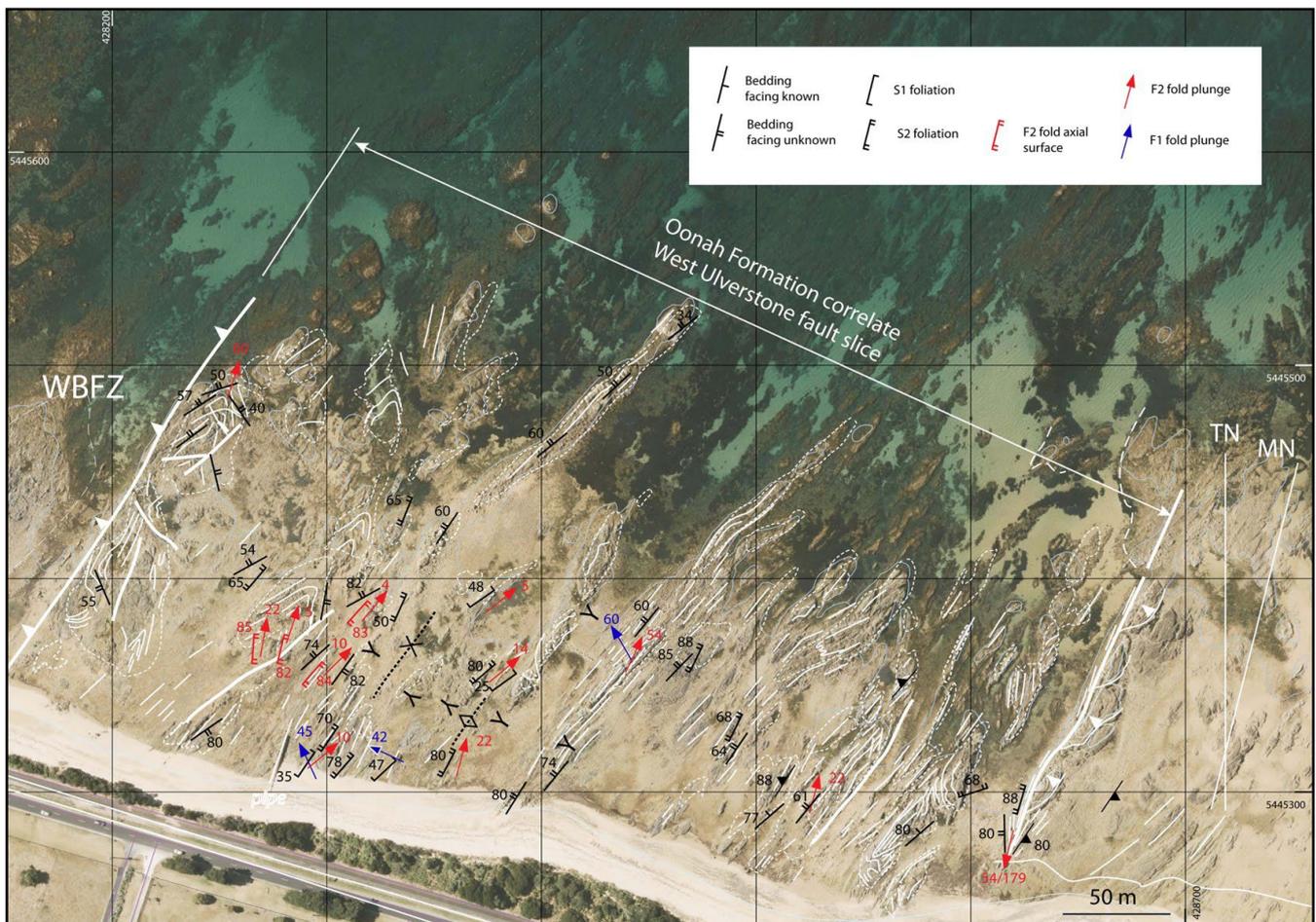


Figure 104. Structural map of the Oonah Formation-correlate sequence in the West Ulverstone fault slice. The map base is a georeferenced Google Satellite image. The outcrop pattern and structural trends, as well as the field stations where structural data was collected. The bedding and foliation (S2) form lines (fine white line traces) trend  $\sim 040^\circ$ - $045^\circ$  and are discordant to the bounding faults shown by the heavy white line traces. The eastern bounding fault of the Westbank Fault Zone (WBFZ), the western fault boundary trends  $\sim 033^\circ$  whereas the eastern, foliation-parallel contact with the Ulverstone Metamorphic Sheet (quartzite/pebble conglomerate sequence) trends  $\sim 025^\circ$ .

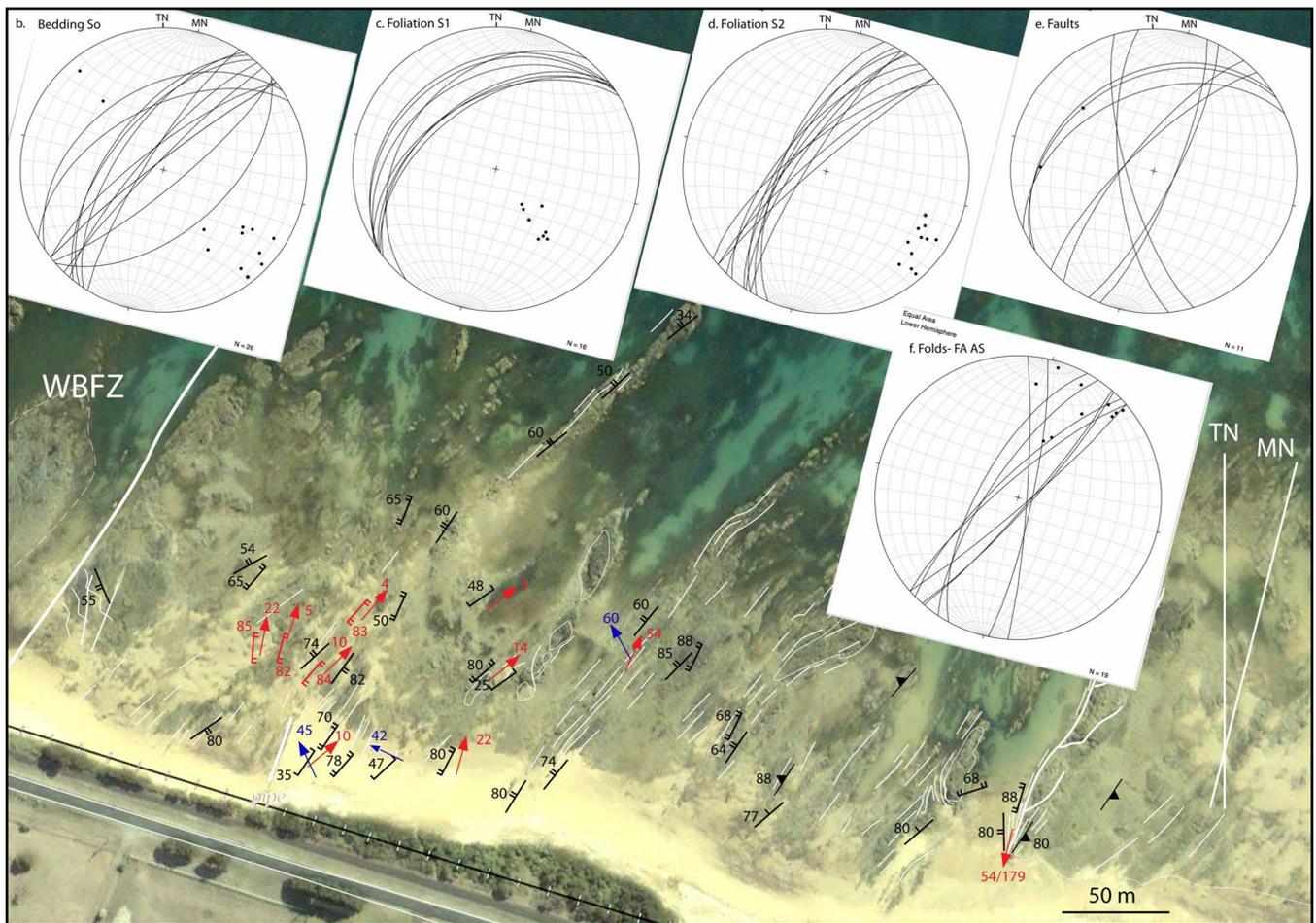


Figure 105. Stereonet plots of Oonah Formation-correlate structural data. a) Google satellite image with plotted structural data (see legend for symbols on Figure 104). b) Bedding great circle traces and poles to bedding. c) Foliation S1 great circle traces and poles to foliation. d) Foliation S2 great circle traces and poles to foliation. e) Fault great circle traces and slickenside attitudes (black dots). f) Fold axial surface great circle traces and fold axis attitudes (black dots).

The eastern contact of the West Ulverstone Oonah L-G fault slice (see Section 4.2.6) is a steep, foliation-parallel interface with apparent welding of strongly foliated and folded black mudstone appears with pebble conglomerate and cherty-sandstone (originally designated as greenschist facies Ulverstone Metamorphics) (Figure 114). The contact is offset by sub-horizontal to gently northwest dipping faults that place sandstone over the black mudstone (Figures 96 and 115). Kinematic analysis of groove-type slickensides indicate small offset (<2-3 m) involving limited back-thrusting to the northwest (lower right sketch inset, Figure 106 and Figure 115). Despite this minor faulting there has been no brittle fault reactivation along the exposed strike length of the contact.

#### 4.2.2 Nature of the Folds

The folds are upright with gentle to moderate north plunges (Figures 105f and 106). They tend to chevron form with narrow rounded hinge zones and long straight or planar limbs (Figures 107 and 108). The dominant upright folds appear to be F2 folds (see folds at contact, Figure 106), although the nature of the axial surface fabrics (Figures 108 and 109) is controlled by the presence of a strong bedding-parallel foliation (Figures 111 and 112).

#### 4.2.3 Nature of the Foliations

The Oonah L-G slice mudstones exhibit a slaty-type cleavage morphology (Scl) in mudstone verging on pencil structure with a spaced disjunctive type foliation (Figures 109 and 110). The pencil character is most common in the hinge zones of the upright second-order folds that dominate the West Ulverstone segment. The penciling is caused by intersection of the bedding-parallel foliation with the sub-vertical S2 cleavage (Figures 111 and 112). The thicker ~1 m thick sandstone beds show a spaced disjunctive cleavage at low (~25°) to moderate (~40°) angles to bedding suggestive of development of a fanning cleavage in sandstones during the folding (Figure 110).

#### 4.2.4 Nature of the Faults

Steep to moderately west-dipping reverse faults characterise the Oonah L-G slice in Fault Slice 2 (Figure 113). The western boundary is the eastern boundary fault of the Westbank Fault Zone with attitude 015/66W (magnetic). Different fault sets occur within the slice (Figure 113a, f) with fault measurement stations shown by the red Station numbers (Figure 113a). Fault kinematic analysis of faults in sandstone bodies (Figure 113c, d and e) show east-west (~096°) and northwest-southeast (~124°) shortening vectors, with a combined vector of ~113°.





Figure 107. Tight, upright, second-order anticlinal fold within black mudstone within the West Ulverstone Oonah L-G slice, West Ulverstone beach.

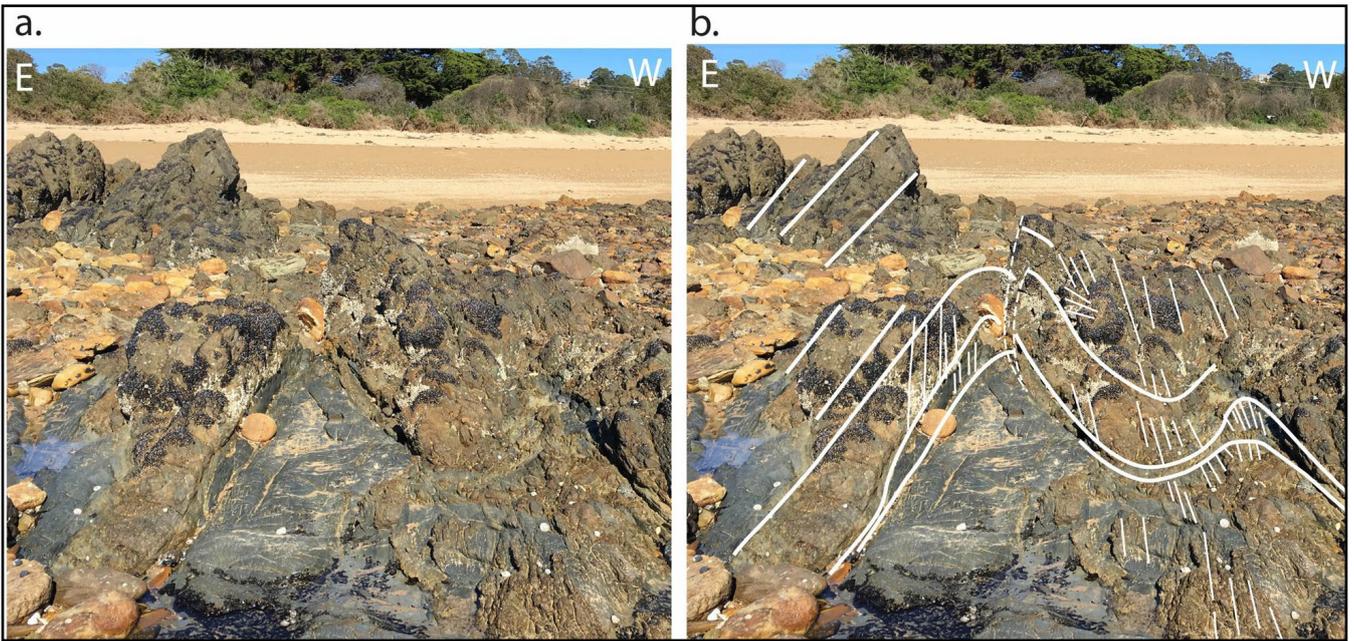


Figure 108. Tight, upright, second-order anticlinal fold within interbedded mudstone and sandstone. of the West Ulverstone Oonah L-G slice, West Ulverstone beach.

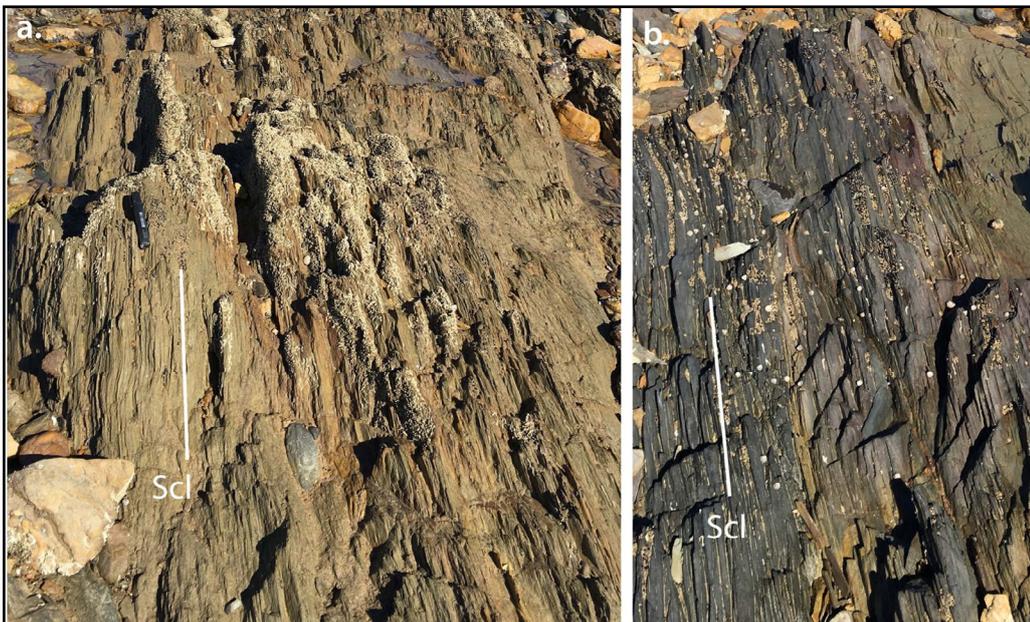


Figure 109. Slaty-type morphology of foliation (Scl) in mudstone of the Oonah West Ulverstone slice. a) Spaced disjunctive type foliation verging on pencil structure due to the intersection of a bedding parallel foliation within the hinge zones of the upright second-order folds. b) Typical slaty cleavage (Scl) appearance in black mudstone.

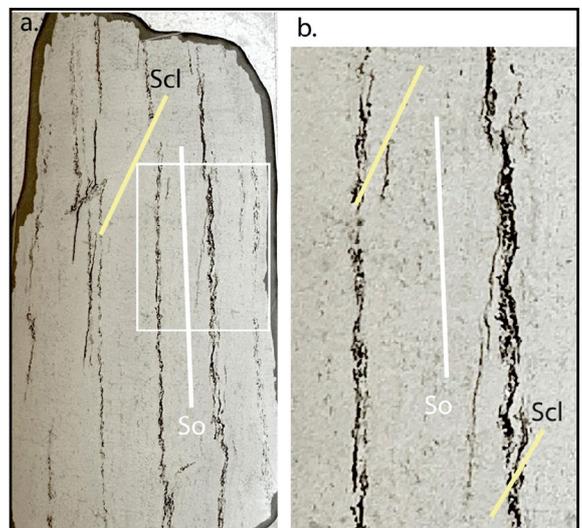


Figure 110 (Left). Steeply west-dipping sandstone layer containing a gently west-dipping spaced cleavage (S1). West Ulverstone beach wave cut platform. Station DG88-471 (see location in the profile, Figure 106).



Figure 111 (Left). Photographs of a deformed mudstone from the West Ulverstone L-G Oonah fault slice (Fault Slice 2). Station DG88-474B. a) Photo of thin section showing intersection of a bedding parallel So fabric with a slaty type cleavage Scl. b) PPL photomicrograph of the grain alignment slaty type cleavage in the mudstone showing dimensional alignment of elongate quartz grains. c) X-nicol photomicrograph of the field shown in (b).

Figure 112 (Right). Thinly bedded siltstone layer from the West Ulverstone L-G Oonah fault slice (Fault Slice 2). a) Photo of thin section showing dark siltstone-like bedding (So) traces obliquely cut by a slaty-type cleavage (Scl) at  $\sim 20^\circ$  to So. b) Enlarged part of the thin section showing an Scl-parallel dimensional grain alignment within the siltstone matrix.



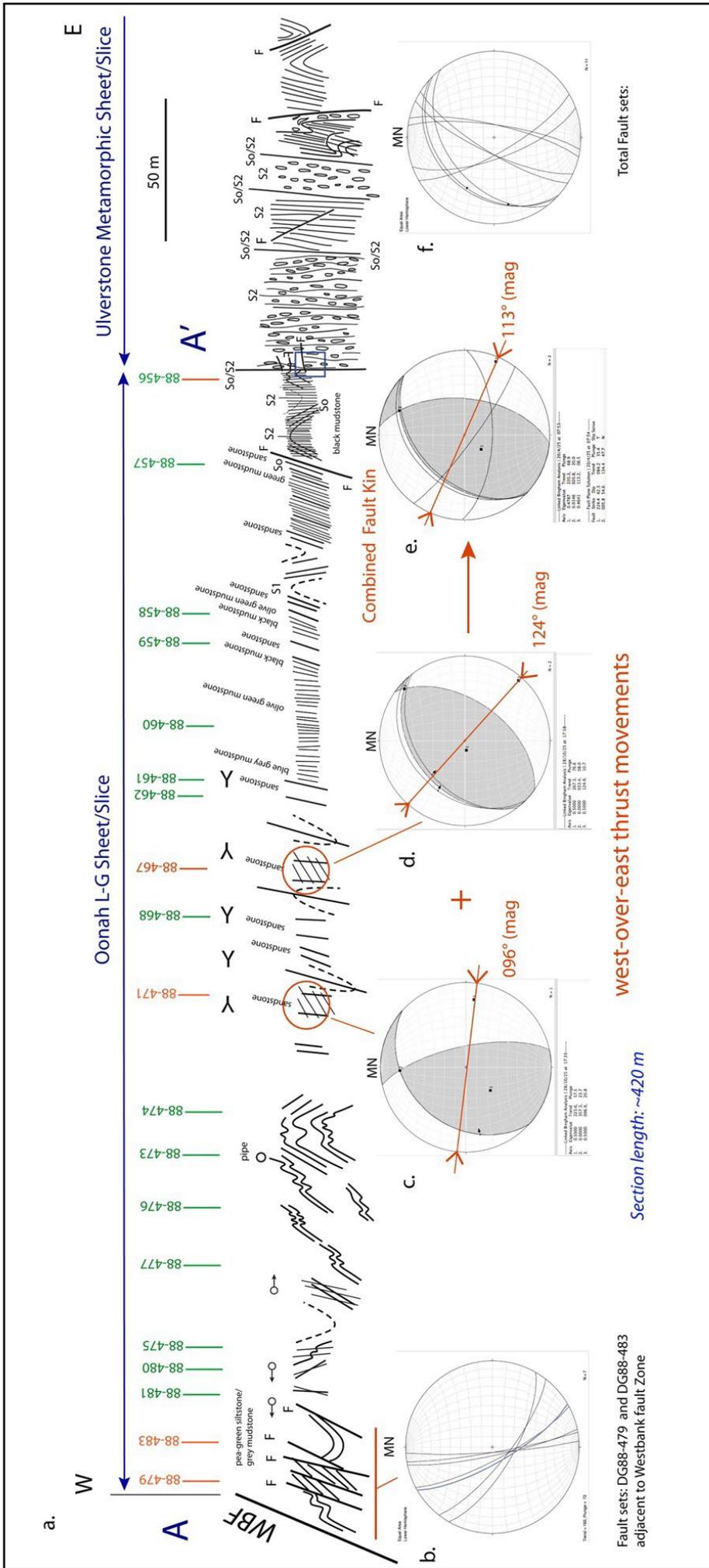


Figure 113. Structural profile of the West Ulverstone slice of the Ononah Sheet faults and fault attitude data. a) Structural profile with locations and areas of faulting. DG88-471 has F: 042/32NNW (mag) and slickenside: 22/258 (mag). DG88-467 has F: 045/35NNW (mag) and slickenside 34/298 (mag) and F: 032/77NW (mag) and slickenside 40/314 (mag). b) Faults in Ononah Sheet adjacent to the Westbank Fault Zone. c), d) and e) are Faultkin TM kinematic stereonet showing a NW-SE compression direction (red line arrows). f) Total fault population for the Ononah Sheet in Fault Slice 2.

#### 4.2.5 Nature of the Contact with the Ulverstone Metamorphic Sheet

The contact of the Oonah sandstone mudstone sequence of the Oonah L-G Sheet is sub-parallel to the strong, steeply, west-dipping S2/Sm foliation in the conglomerate-intercalated quartzite of the Ulverstone Metamorphic Sheet (Figures 106 and 114). The contact has a "welded" character with a wedge of strongly foliated, black mudstone of the Oonah Sheet containing isoclinally folded quartz veins (Figures 114b, c). The mudstone is juxtaposed with a tightly folded sandstone layer where the folded bedding (So) is truncated by the foliation within the black mudstone at the contact (Figure 114c), but the

early S1 cleavage appears continuous across the interface (Figure 114c).

There is no apparent younger, Devonian fault reactivation of the contact unlike the Singleton Fault Zone contact in Fault Slice 1. There, a zone of younger, steep faults in the Oonah Sheet (Singleton Fault hanging wall) are activated above a footwall ramp in the Goat island Conglomerate. In contrast, the contact in Fault Slice 2 is only slightly offset by a series of flat faults (Figures 106 and 115). These faults dip gently to the northwest and combined with slickenside data give an east-over-west thrust sense formed by (Figures 115b and 116b).

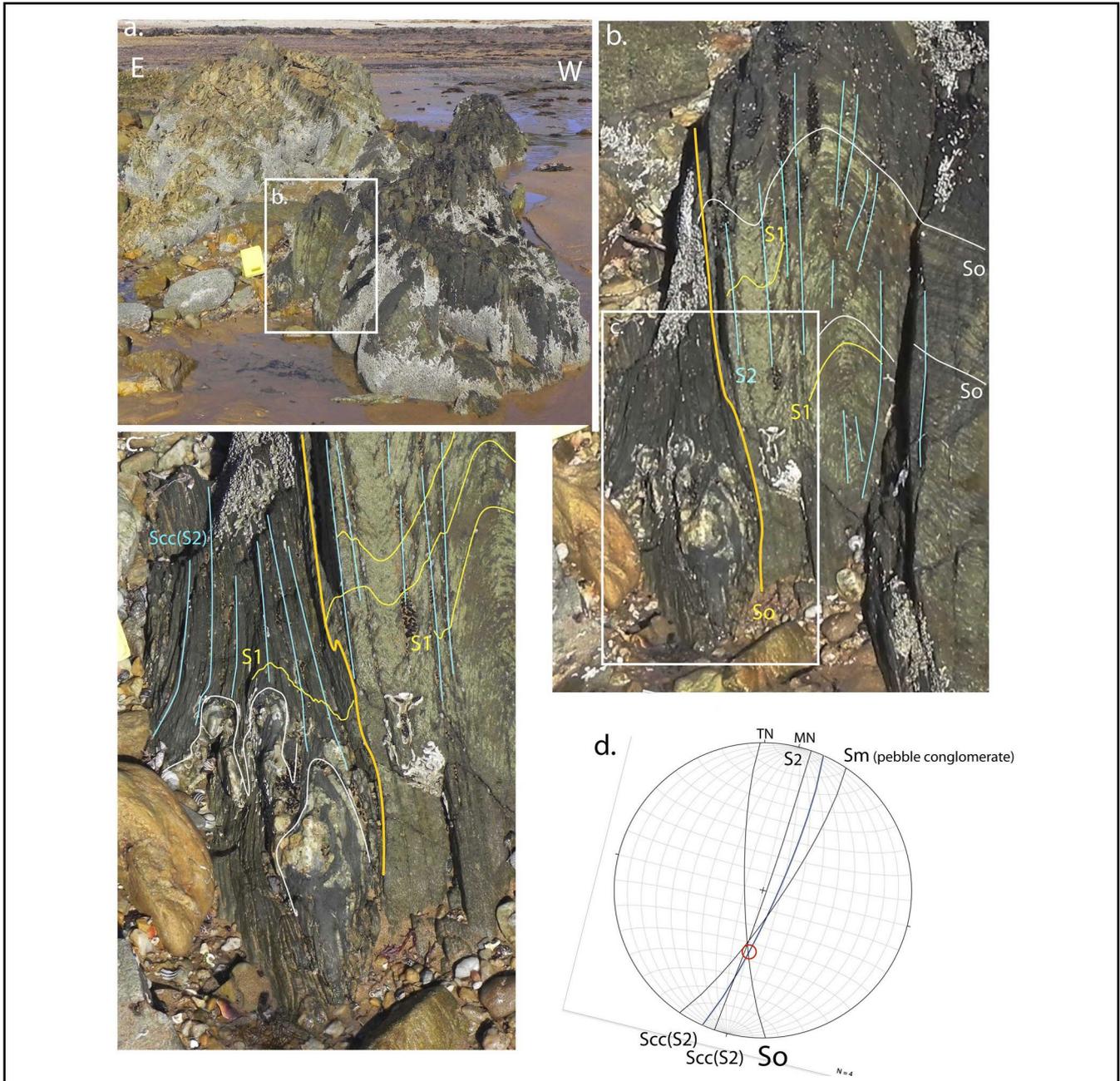


Figure 114. Deformed, "welded" contact between the Oonah L-G slice (subgreenschist mudstone and interbedded sandstone sequence) on the west (photo right) and the deformed, greenschist facies, pebble conglomerate/quartzite sequence on the east (photo left). a) View of the deformed contact showing the light brown conglomerate (left) and the dark-coloured mudstone-sandstone (right). b) Enlarged view of contact showing strong to intense S2 foliation subparallel to the conglomerate-mudstone interface, isoclinal folding of a laminated quartz vein in a transposed wedge of dark mudstone where the bedding (So) in the laminated sandstone is truncated at the interface but the early S1 cleavage appears continuous across the interface. c) Enlarged annotated view of the transposed dark mudstone layer with the various foliations highlighted. d) Stereonet plot of foliation attitudes, including the S2 foliation in the mudstone and folded sandstone, and the foliation Sm within the pebble conglomerate. The So great circle trace is the approximated contact (structural interface) between the pebble conglomerate and the mudstone shown in (a).



Figure 115. Low angle faults offsetting the pebble conglomerate-cherty quartzite (Ulverstone Metamorphics/mudstone (Oonah) contact along the eastern boundary of the Oonah West Ulverstone fault slice.

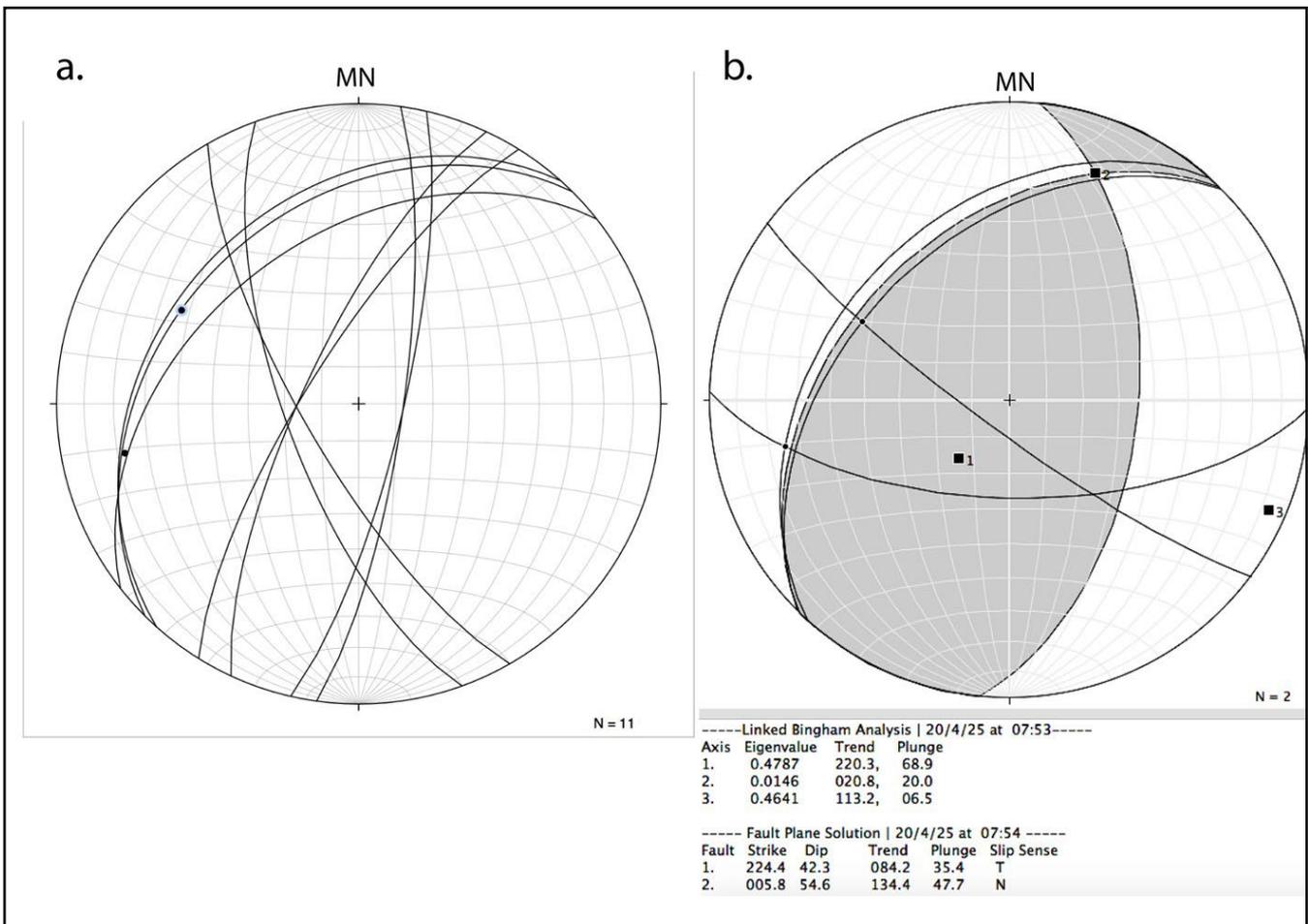


Figure 116. Faults within the West Ulverstone Oonah L-G fault slice. a) Great circle traces of four fault sets within the Oonah slice. b) Kinematic data for the low angle faults within and bounding the sandstone channel pods/layers within the Oonah L-G fault slice (see Figure 113).

#### 4.2.6 Structure of the West Ulverstone Slice of the Ulverstone Metamorphic Sheet

This slice of the Ulverstone Metamorphic Sheet that is part of Fault Slice 2 consists of structurally intercalated pebble conglomerate, quartz-mica schist, quartz-mica phyllite and minor quartzite (Figure 117). The sequence has largely homoclinal, steep west-dip but is folded in part (Figure 118 and 119). The folds are moderate to steeply plunging and show plunge changes along the length of a folded layer (Figure 118). The dominant foliation within the sheet is S2. The intercalated quartz-mica phyllites show a strong bedding parallel foliation So/S1 that is tightly folded (Figure 118) or weakly crenulated (Figure 119).

#### 4.3 Bass Highway Transect of the West Ulverstone Imbricate Zone

The Bass Highway provides a southern transect across the West Ulverstone Imbricate Zone (Figures 73 and 120). Two major cuttings on the south side of the Bass Highway west of the West Ulverstone Interchange provide exposure through the southern continuation of the Imbricate Zone, with a missing segment as an erosional gap (Figures 121, 122 and 123).

The major faults in these Bass Highway cuttings are continuations of faults exposed on the coast (Figures 72 and 73). The faults are steeply dipping, brittle fault zones, commonly consisting of zones of multiple faults (Figure 120).

The West Ulverstone Oonah L-G slice between the Westbank Fault and the Ulverstone Fault (Fault Slice 2) is folded into a series of broad open anticlines and synclines with a weak, north-trending and west-dipping, axial surface crenulation cleavage (segment DG89-25, Figure 123). Approaching the Westbank Fault (segment DG88-368, section B-B', Figure 122) a large anticlinal fold in the Oonah is overturned to the west with steeply, east-dipping Oonah in the fault footwall as part of the overturned? fold limb (inset upper left, Figure 122).

Approaching the projected Ulverstone Fault (east side of Figure 120) two sets of crenulation cleavages are associated with both northeast (020°-030°) trending and north (175°-180°) trending folds (segment DG89-24, Figure 123). These fold sets have gentle south plunges (stereonet b, c, and d, Figure 123). The northeast trending crenulation cleavage Scc appears to refold the north trending Scc.

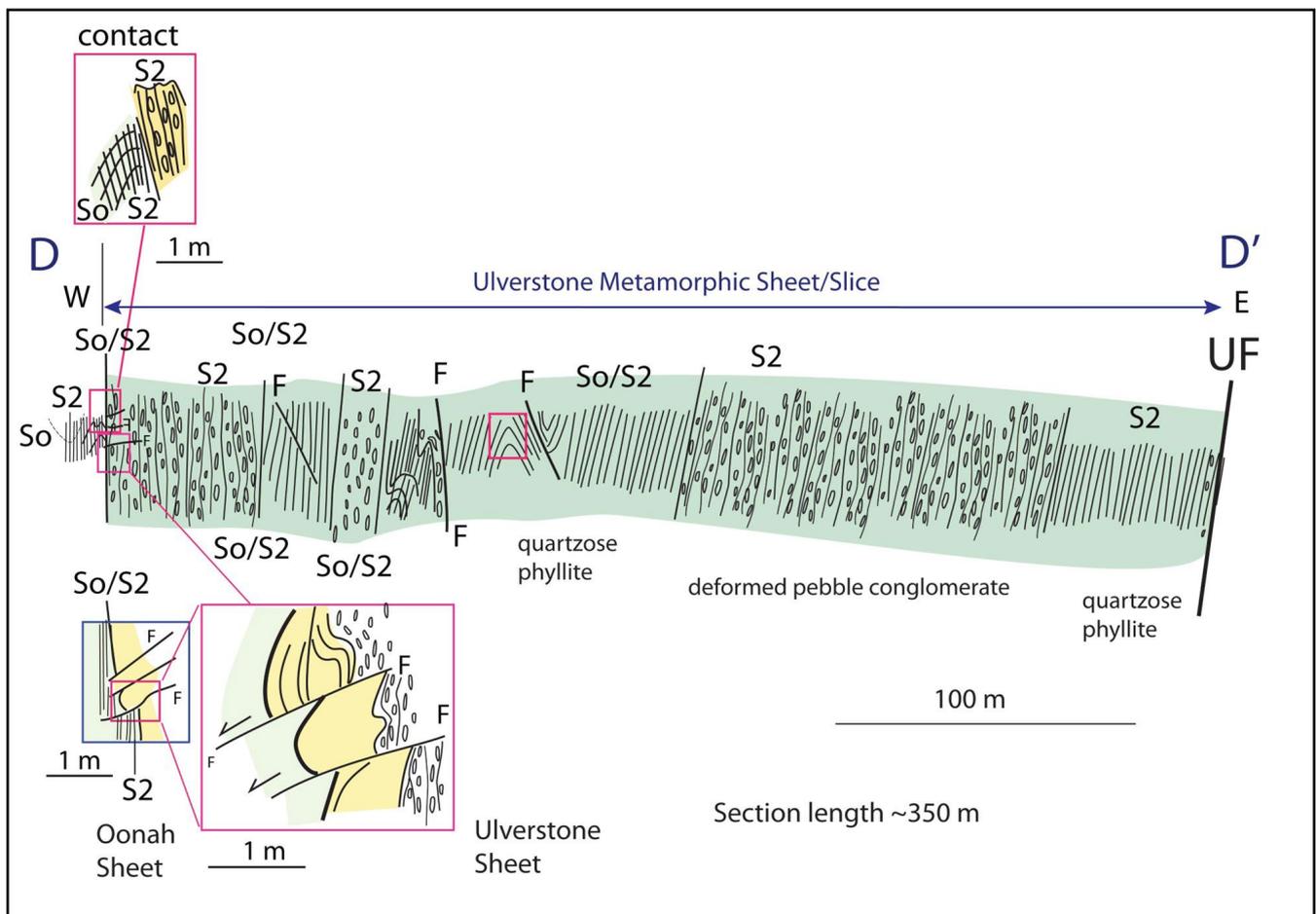


Figure 117. Sketch structural profile of the Ulverstone Metamorphic Sheet within Fault Slice 2 of the West Ulverstone Imbricate Zone. The enlargements on the western (left) side of the profile show the structural relationships at the interface with the Oonah L-G Sheet. There is no apparent fault along the contact. The slice is strongly to intensely foliated with homoclinal, steep west-dip.

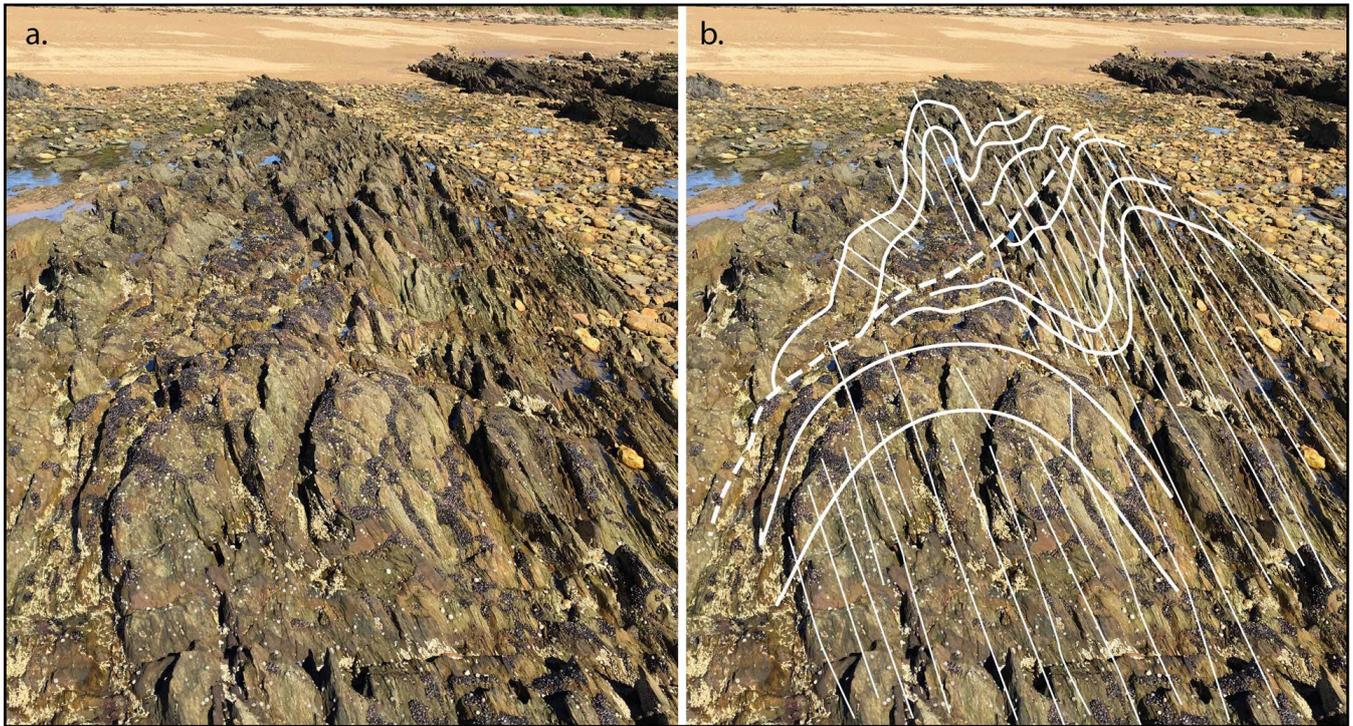


Figure 118. Complex disharmonic F2 folding within thin-bedded, quartz-mica psammitic schist interbedded with quartz-mica phyllite. The dashed white line trace is an interpreted fault that offsets parts of the fold train. The view is looking to the south. The folded layer shows fold plunge changes from  $45^{\circ}/010^{\circ}$  to  $68^{\circ}/025^{\circ}$  along the length (Station DG88-443).

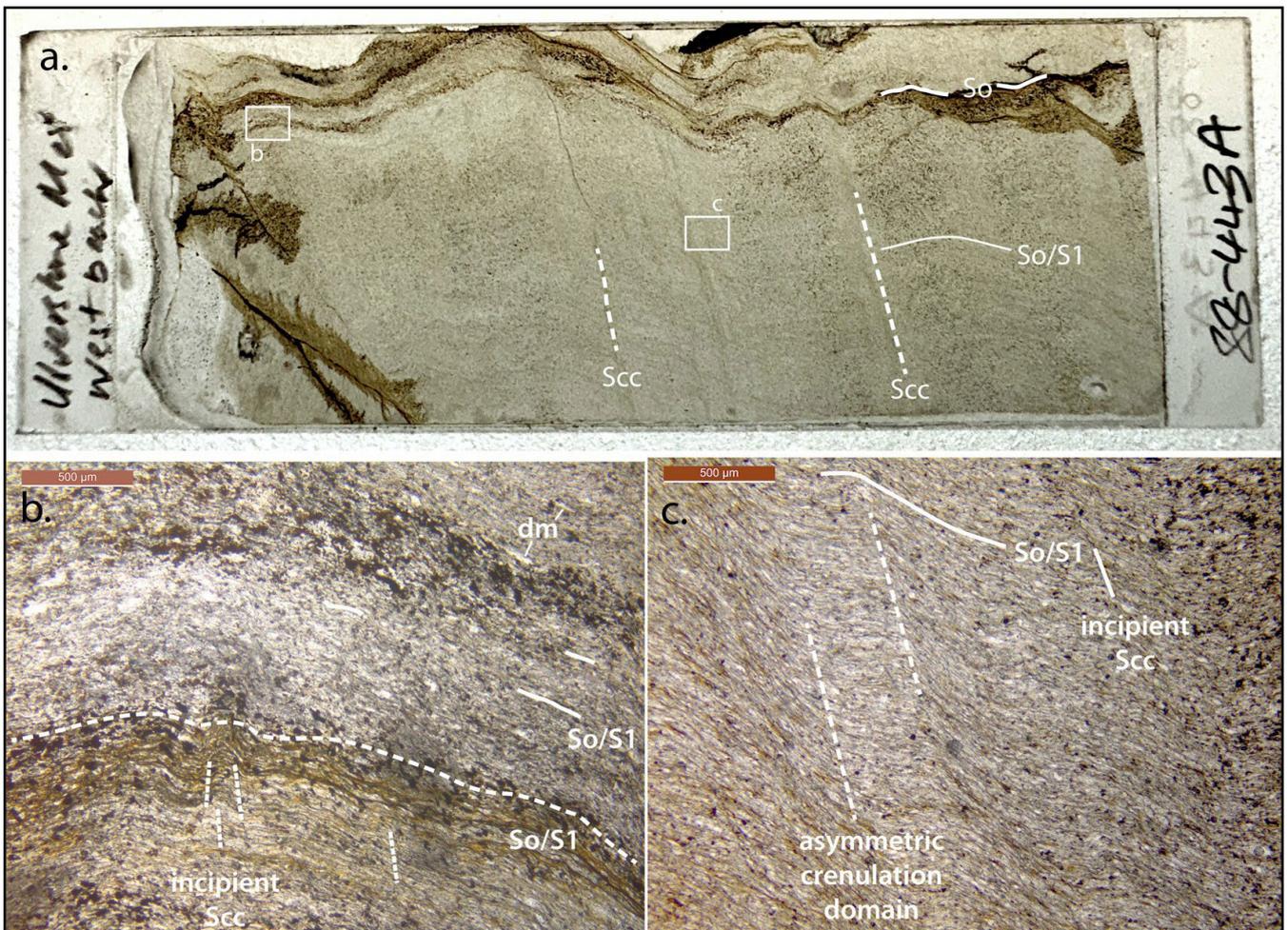


Figure 119. Deformed interlayered mudstone-siltstone phyllite from the West Ulverstone L-G Oonah Correlate fault slice (Station DG88-443A; see Figure 118). a) Photo of thin section.

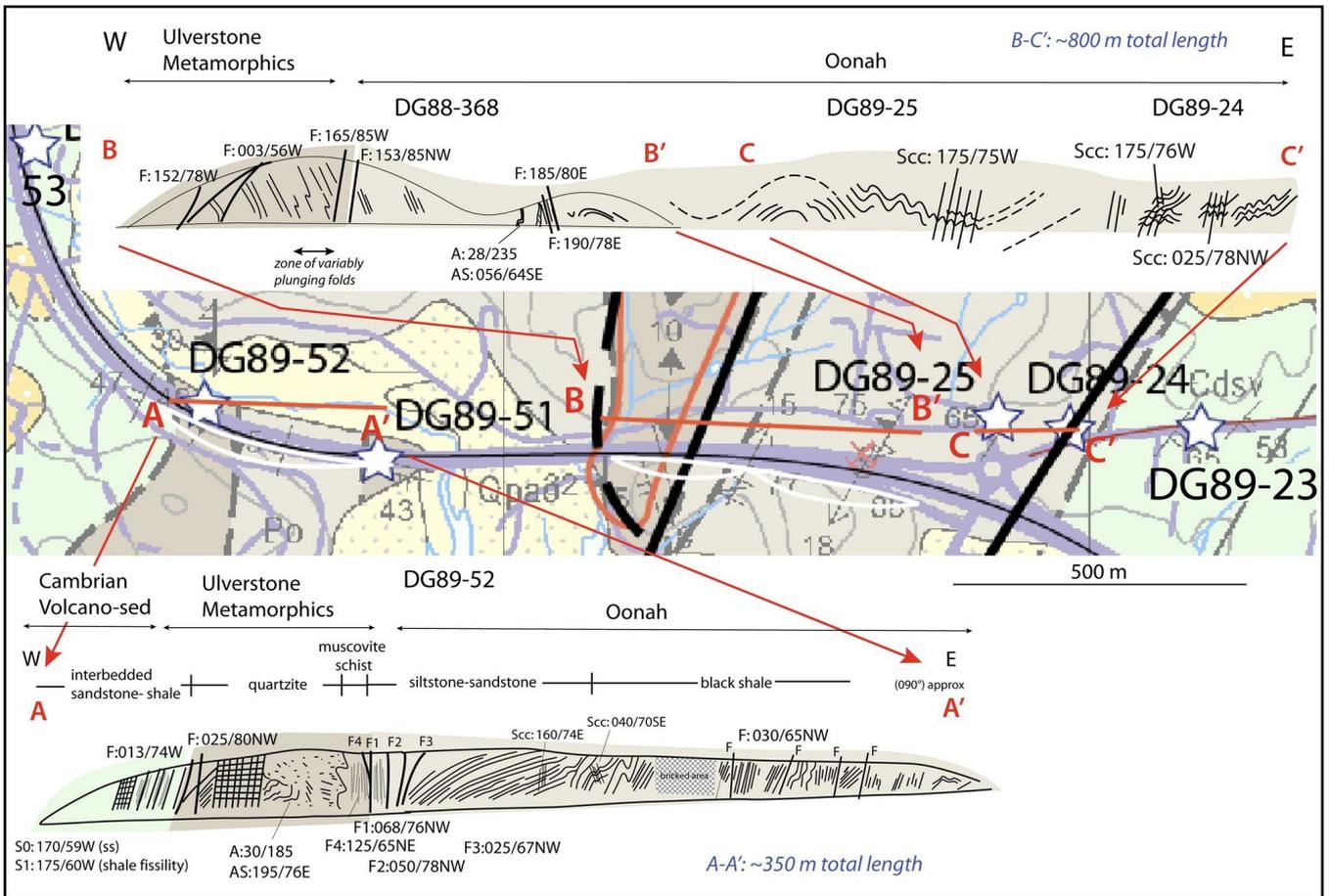


Figure 120. Profile location map for an ~1.2 km structural profile across the southern part of the West Ulverstone Imbricate Zone. Profile A-A' is Figure 121. Profile B-B' is Figure 122. Profile C-C' is Figure 123.

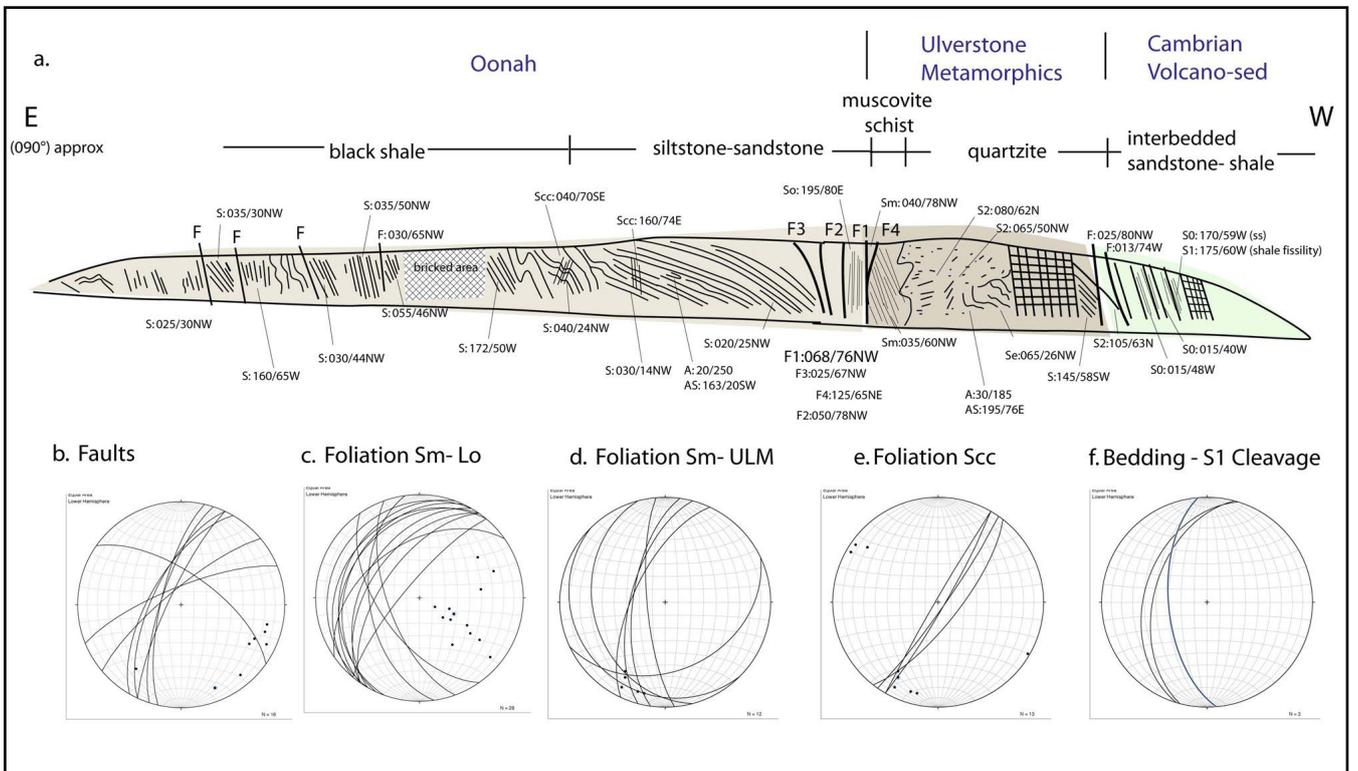


Figure 121. Sketch structural profile of the West Cutting (see red WC, Figure 72) the westernmost Bass Highway road cutting past the West Ulverstone Interchange (for location see section A-A', Figure 120). The cutting extends for approximately 450 m on the south side of the freeway. The view is looking south onto the cutting face. Formlines in Sm and So/Sm highlight the structure. The stereonets show the attitudes of structural elements measured in the cutting.

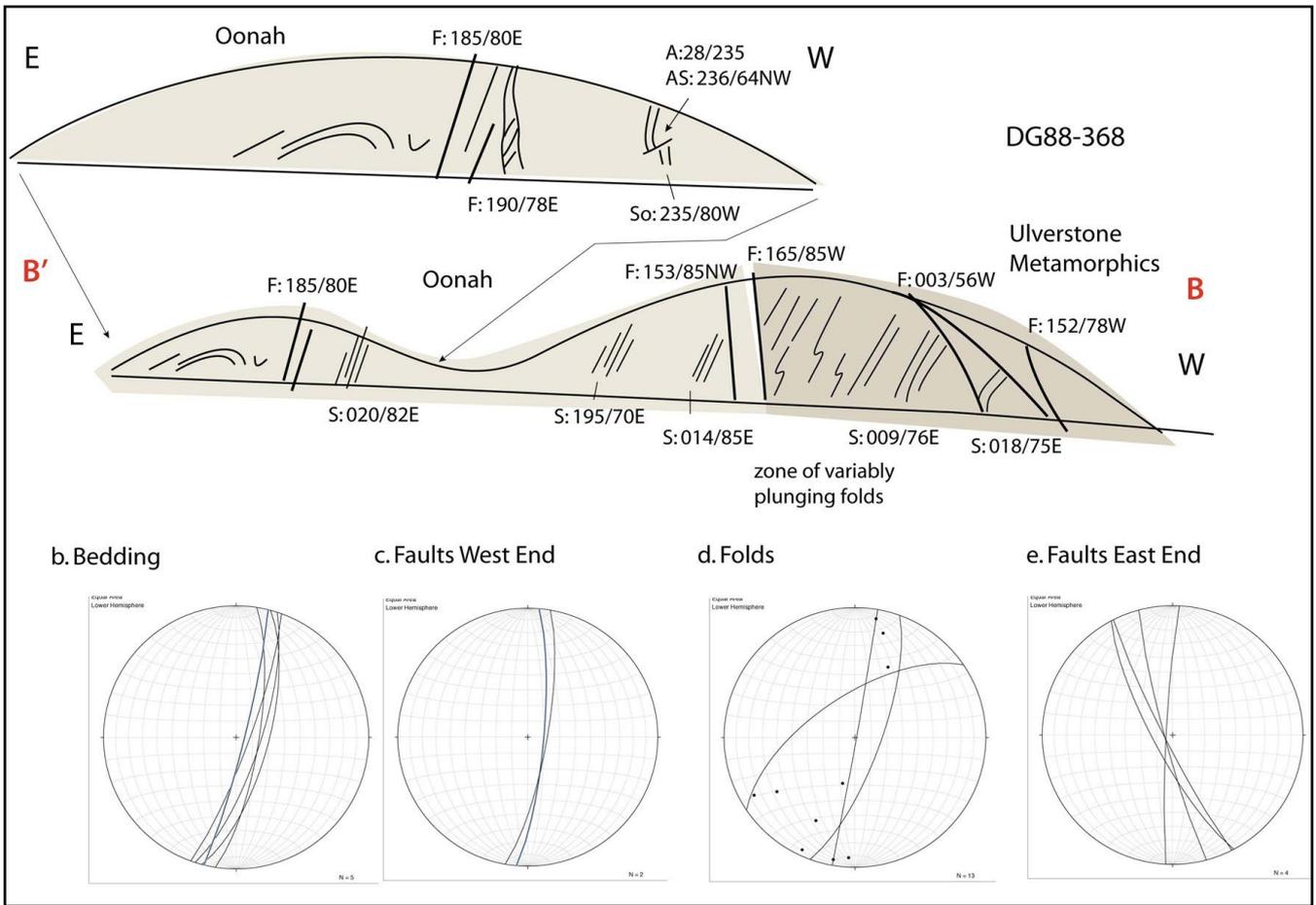


Figure 122. Sketch structural profile of the East Cutting (see red EC, Figure 72), the easternmost Bass Highway road cutting at the West Ulverstone Interchange and access road (for location see section B-B', Figure 120). The cutting is on the south side of the Freeway. The stereonet shows the attitudes of structural elements measured in the cutting.

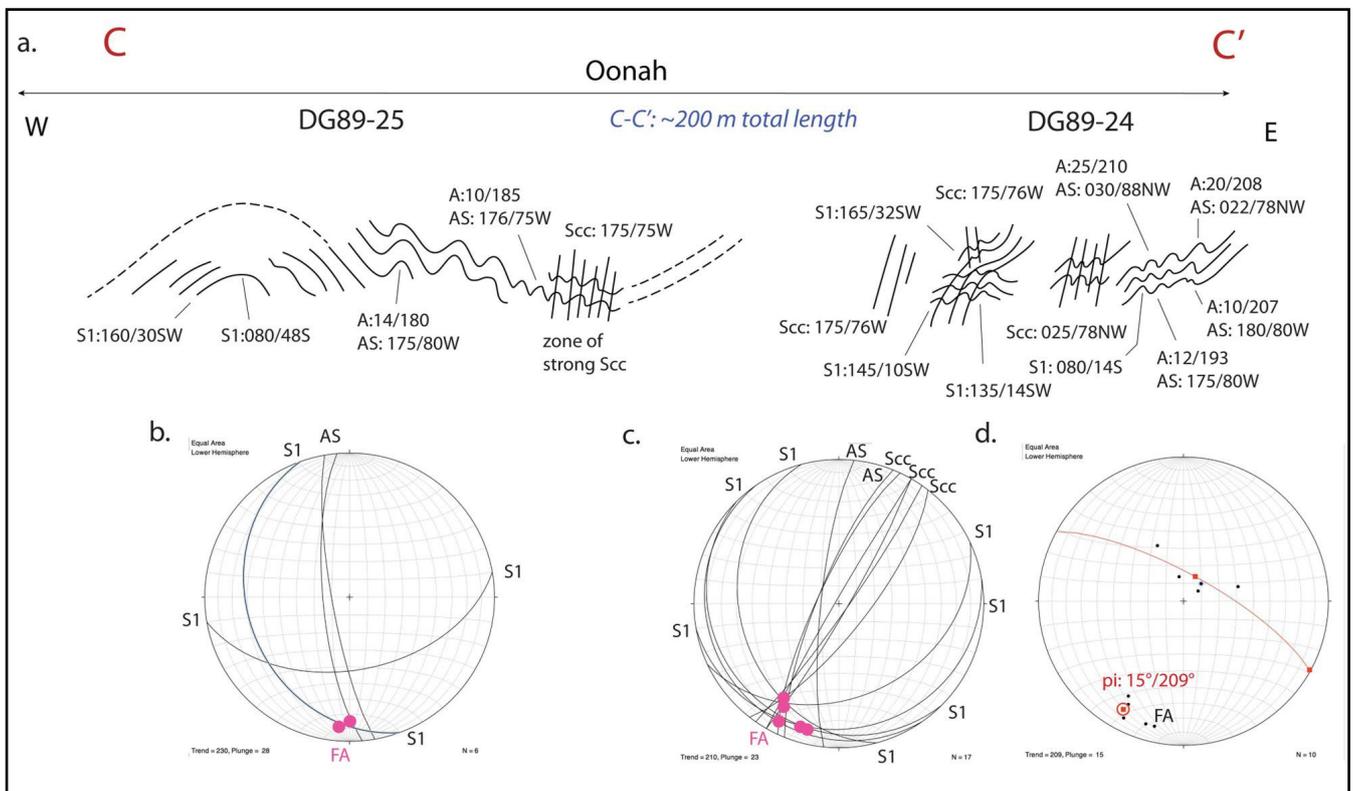


Figure 123. The easternmost part of the Bass Highway structural transect (for location see section C-C', Figure 120). The sketch profile is based on two cutting exposures on the West Ulverstone interchange connection. Segment DG89-24 is the outcrop of the Oonah L-G slice closest to the inferred position of the Ulverstone Fault (black line, Figure 120).

#### 4.4 Faults and Fault Zones of the Imbricate Zone

The presence of broken formation and scaly mudstone matrix *mélange* with blocks of Togari Group suggests these fault segments, including the Westbank Fault Zone and the Ulverstone Fault Zone are part of the basal interface of the allochthonous Oonah sheet low-grade metamorphics sheet during emplacement over the underlying high-grade Forth Metamorphic sheet (Figure 124).

##### 4.4.1 The Singleton Fault Zone

The nature of the Singleton Fault is enigmatic with its character and significance debated (see Turner, 1989, p.3; Berry and Gray, 2001). The Goat Island locality is an anomaly both within and along the Singleton Fault showing complicated geometrical form (Figure 79). Elsewhere along the fault, or contact between the Oonah L-G Sheet and the greenschist facies Ulverstone Metamorphic Sheet, it is a steeply west-dipping fault (Figures 76, 77 and 79) or zone of steeply dipping faults (Figure 125). At Goat Island the contact between the Oonah Formation (formerly the Burnie Formation of the Rocky Cape Group) and the Ulverstone Metamorphics was mapped and originally defined by Burns (1963a, 1964) as a fault (the Singleton thrust), with Oonah thrust eastwards over Ulverstone metamorphics. This contact and another at Mt Remus with similar stratigraphic relationships (Spry, 1962) have also been considered as unconformities or faulted unconformities (cf. Turner, 1989, p.30).

There are distinct differences in degree of deformation and metamorphism across this contact. Bedding is still preserved in the Oonah Sheet, whereas in the Ulverstone Metamorphic Sheet the main lithological boundaries are generally parallel to the dominant foliation S2. Sandstones in the Oonah Sheet still retain their detrital character but show a spaced grain alignment fabric, whereas those in the Ulverstone Sheet have been recrystallised to show a distinct metamorphic fabric. Nothing indicative of an unconformity, such as fluvial conglomerate facies, has been observed.

The boundary must be a fault as structures in both the footwall (Ulverstone Metamorphic Sheet) and hanging wall (Oonah Sheet) at Goat Island are clearly truncated by it (Figures 125, 126, 127 and 128). Also, the Oonah Formation is significantly more faulted than other exposures of the Oonah Sheet further west. Burns (1964, p.152) originally described the fault/"thrust" plane as a smooth, polished surface overlain by a chaotic breccia made up of 1-7 m sized blocks of sandstone and mudstone (Oonah Formation) and pebble conglomerate". The breccia shows randomly oriented blocks of Ulverstone Metamorphics containing S2 and Oonah mudstone containing bedding (So), in a patchwork quilt arrangement with negligible matrix (Figure 129).

However, there are problems with this interpretation. In the rock platform at Goat Island, the Highway cutting, and the gravel quarry at Singleton Point the contacts where observed were steep (dips > 60°). Furthermore, the contact at Goat Island is not simple, and consists of a nar-

row, curved east-west to northeast-trending zone of brecciated Oonah Sheet that "wraps" around the south end of Goat Island. At low tide the brecciated zone provides access to Goat Island and although generally covered by conglomerate debris, parts of the breccia can be seen on the southeast side of the island (Figure 129).

Given the outcrop pattern what does Goat Island represent? Is it a block of Ulverstone Metamorphics trapped within a 20 m wide, steeply dipping fault, an inlier of the Ulverstone Metamorphic Sheet surrounded by Oonah Formation of the Singleton thrust sheet, or is it a high along a low to moderately dipping fault plane where the brecciated beds now represent a tongue exposing the lowest levels of the Singleton thrust sheet between the highs in the thrust plane?

At Goat Island the Oonah Sheet in the fault-hanging wall has a tongue-like projection of breccia overlying the footwall of pebble conglomerate (Figures 76 and 130). The projection is now preserved as a thin breccia zone within a topographic low or depression along the Singleton Fault surface. The lateral boundaries of the breccia tongue are east-west trending, steeply dipping faults that must flatten eastwards and close out into a spoon-shaped geometry (Figure 130). This has created a complex fault geometry involving a re-entrant in the main, steeply west-dipping Singleton Fault where the fault curves into steeply dipping, east-west trending lateral ramps. These lateral segments must flatten and swing into a close-out of the breccia to create the spoon-shaped fault geometry (Figure 130).

The breccia consists of a series of fault-bounded blocks derived from both the footwall (pebble conglomerate) and the hanging wall (mudstone and sandstone). They have variable sizes and shapes, are disoriented with respect to the enclosed bedding (Oonah Sheet blocks) or foliation (Ulverstone Sheet blocks) (Figure 129). The breccia "tongue" is bounded laterally by steep, interconnected faults forming an array within the breccia zone (Figures 125, 126, 127 and 128). No breccia matrix, such as scaly-mudstone matrix *mélange* as observed in both the Westbank and Ulverstone Fault Zones, has been located between the blocks at Goat Island.

##### 4.4.2 Westbank Fault Zone

The Westbank Fault Zone is an assemblage of deformed Neoproterozoic Togari correlate blocks in a 200 m wide zone on the footwall of the Westbank fault (015°/80°W mag) that defines the western margin of the zone. The Westbank Fault is a complex fault zone defined by a train of west dipping slabs of black limestone, lithic sandstones, pebble conglomerate, dolomite, black shale, and maroon and green mudstones (Figure 131a and b). The blocks, up to 150 m in length, are bounded and truncated by numerous faults, where the major faults are linked by sigmoidal oblique faults to form a complex intersecting network (Figure 132c). The zone was originally referred to as 'chaos' or tectonically deformed breccia (Burns, 1964; Seymour and Vicary, 2010).

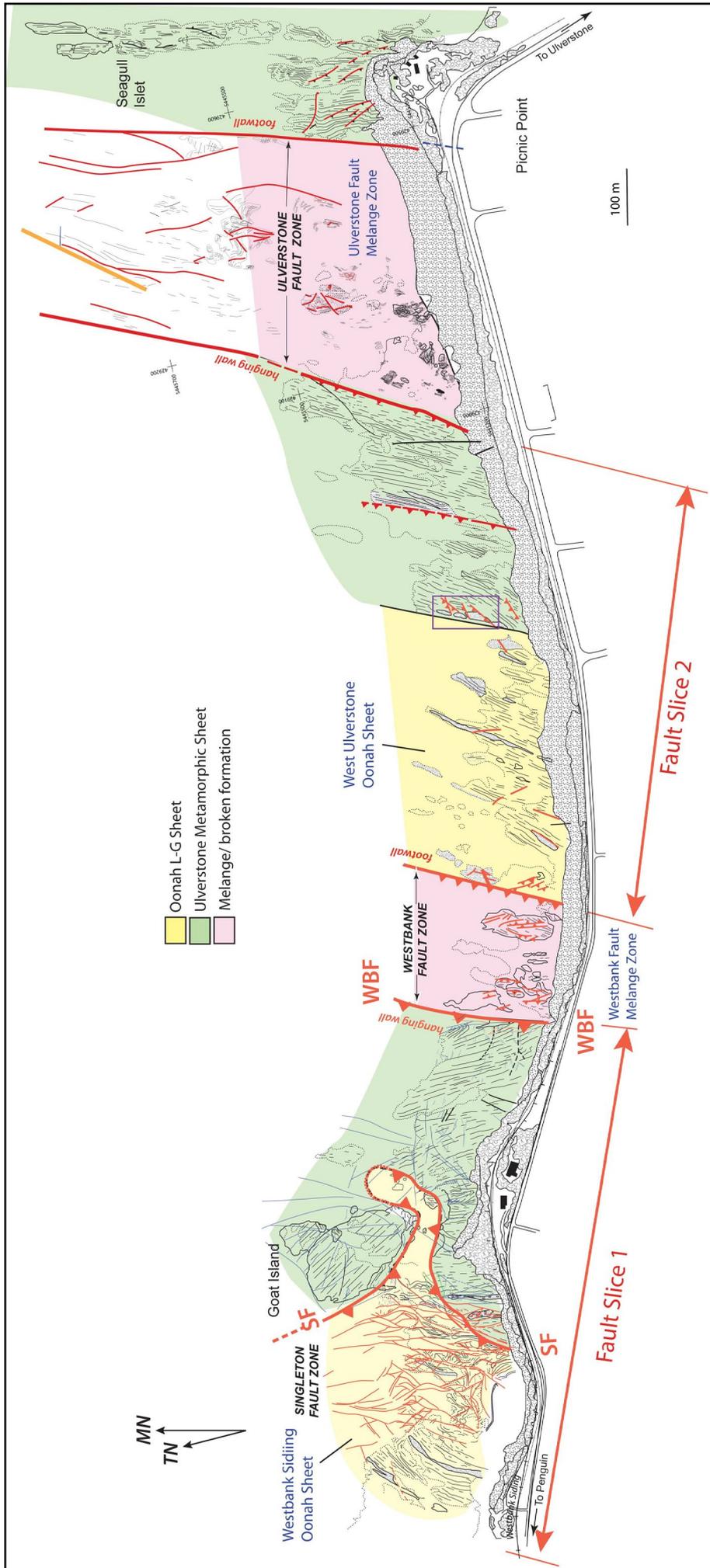


Figure 124. Fault map of the West Ulverstone Imbricate Zone showing Fault Slices 1 and 2. The map represents the coastal platform from Westbank Siding to Picnic Point-Seagull Islet. Red lines are major fault traces. Three main Fault Zones are shown as part of, or separating, the two main fault slices of the West Ulverstone Imbricate Zone (designated Slices 1 and 2).

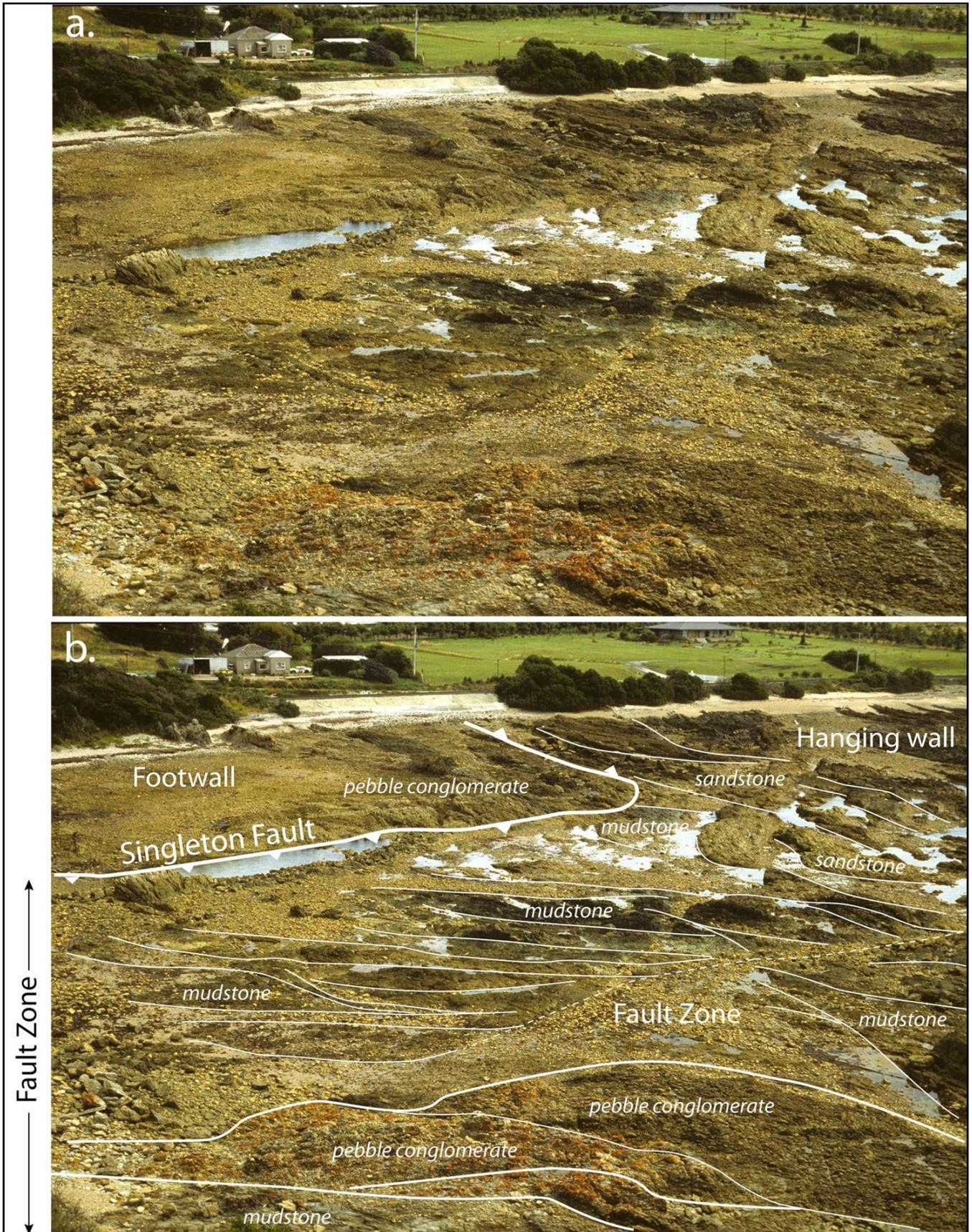


Figure 125. View towards Westbank Siding taken in January 1989 from the South Summit of Goat Island. The wave-cut platform shows the southern flank of the Singleton Fault Zone, the bend in the Singleton Fault to a south-trend, and the heavily faulted, fragmented nature of the Oonah hanging wall transitional into the segmented blocks of sandstone and mudstone within the tongue-like projection of the Oonah Sheet onto the pebble conglomerate of the Ulverstone Metamorphic sheet.

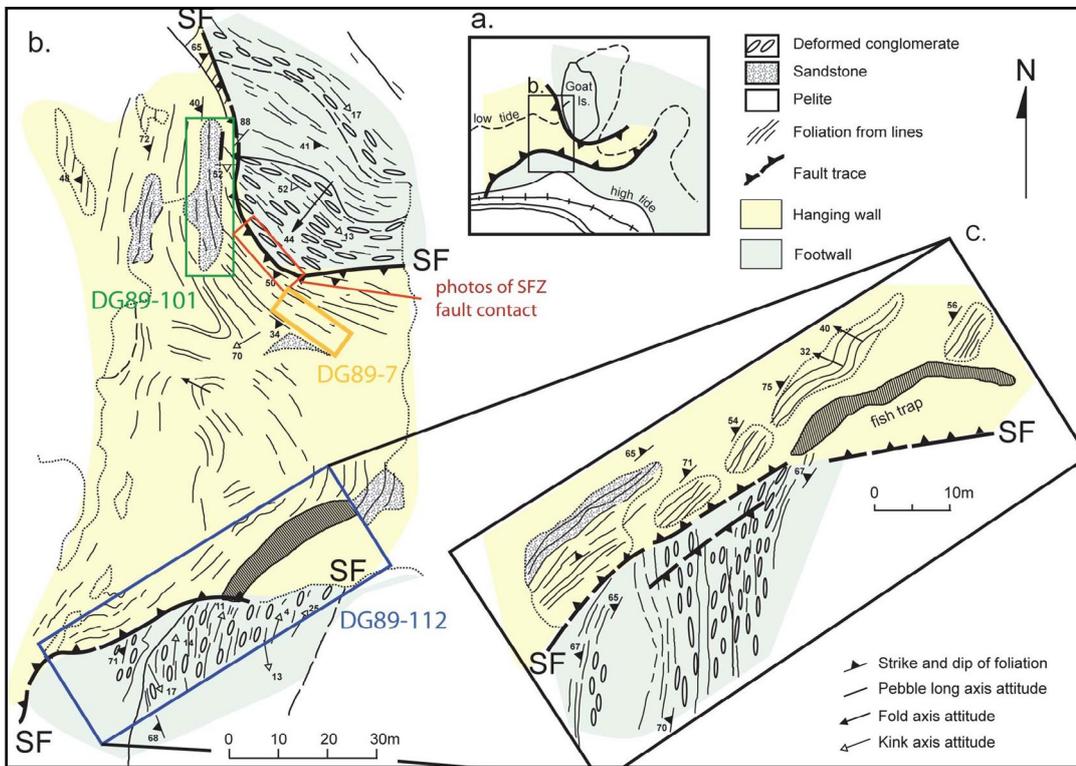
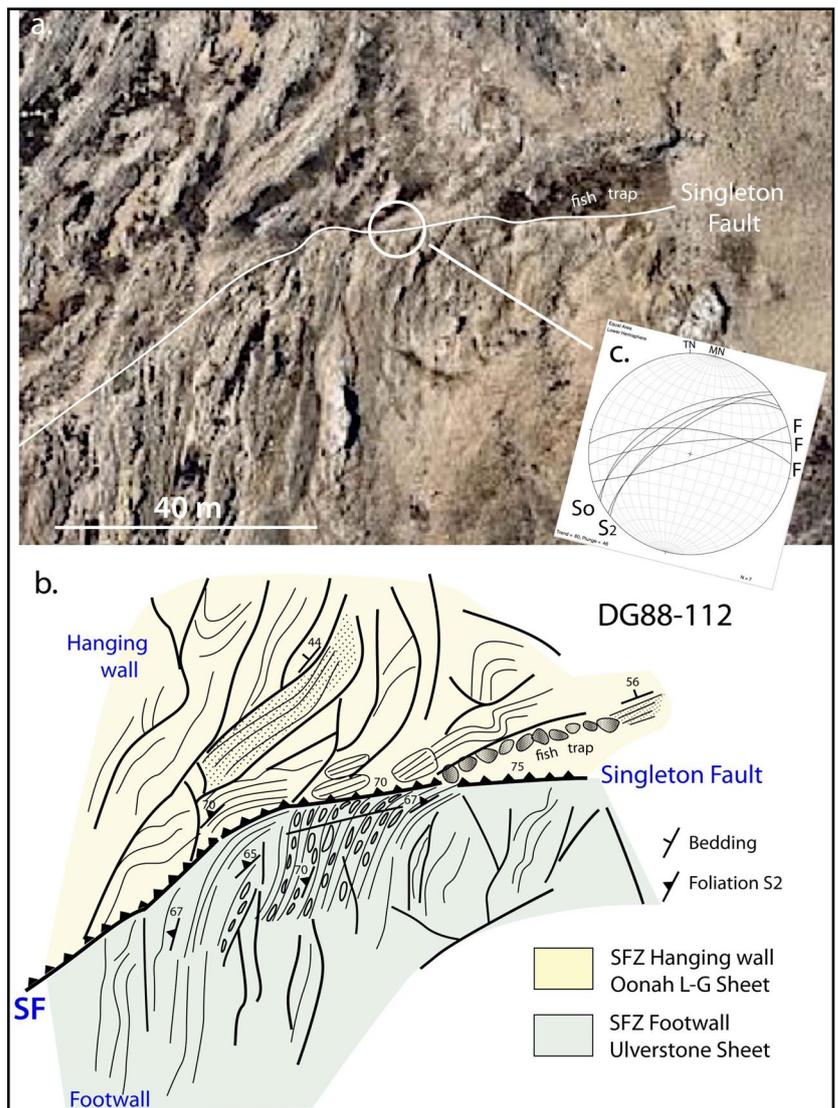


Figure 12(Above). Structural map of the Singleton Fault showing the nature of the exposed fault contacts and the structure within the immediate hanging wall (Oonah Sheet) and immediate footwall (Ulverstone Metamorphic Sheet). For more detail of the southern contact see Figure 127.

Figure 127. Singleton Fault structural relationships along the southern fault trace. a) NearMapTM image of Singleton Fault trace showing structural discordance between the Oonah sandstone-mudstone sequence in the hanging wall and the foliated pebble conglomerate-quartzite-phyllite of the underlying Ulverstone Metamorphic Sheet. b) Modified DG88-112 structural sketch map of the area depicted in (a). Note the S2 foliation in the pebble conglomerate is deflected at the fault trace indicating a relative component dextral shear component along the Devonian reactivated, steeply north-dipping Singleton fault. This is the southern contact of the steep-sided, tongue-like projection of very low-grade Oonah sandstone and mudstone sequence (hanging wall) emplaced over Goat Island pebble conglomerate (footwall). c) Stereonet with great circle traces of bedding So (HW) and foliation S2 (FW) and fault attitude measurements on part of the fault trace.



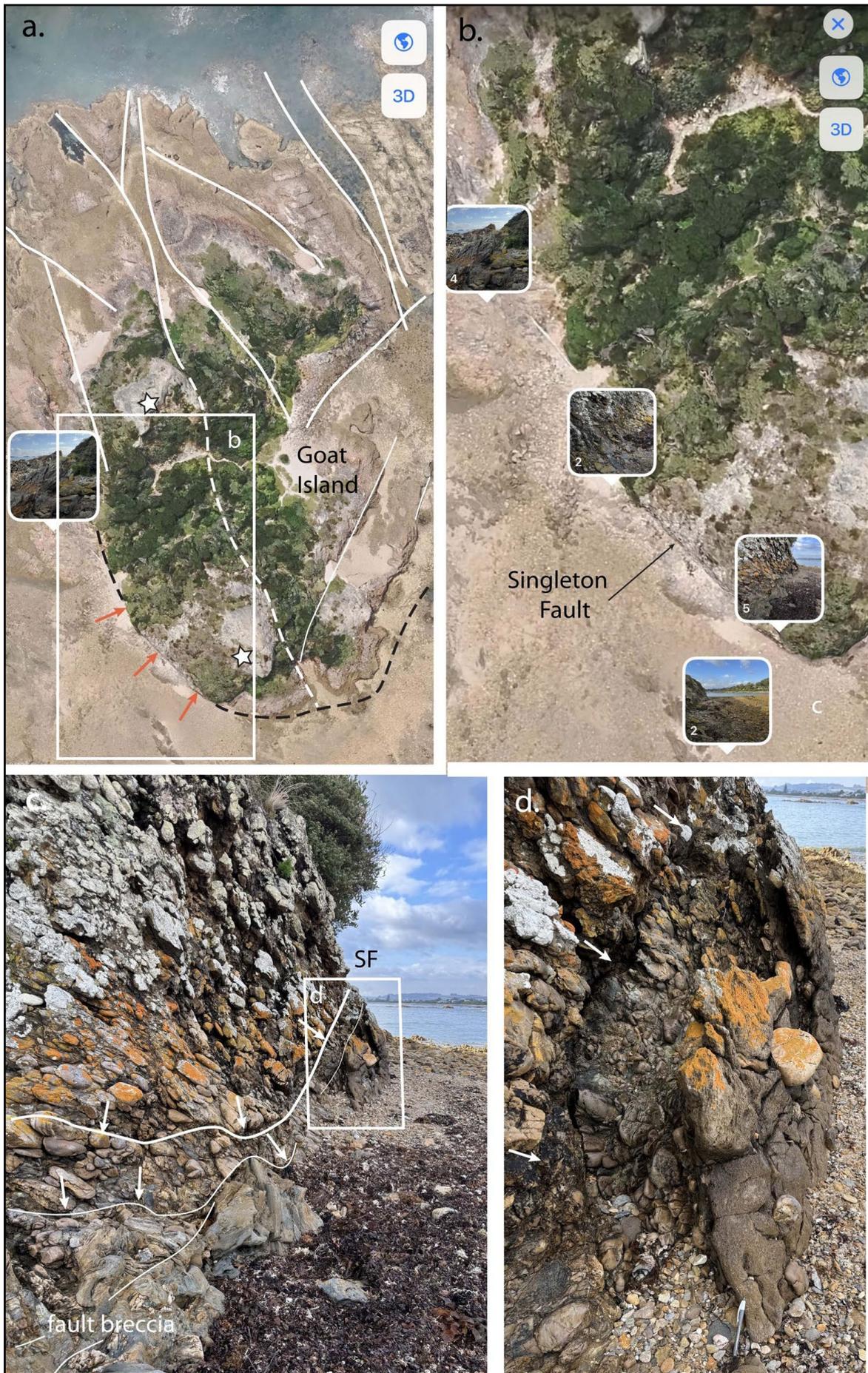


Figure 128. Steeply-dipping nature of the Singleton fault along the southwest side of Goat Island. a) and b) Google satellite images of Goat Island showing the northern fault trace and positions of the photographs (Apple Iphone photo location map). c) and d) show the fault contact in the southwest flank of the Island. Overall the fault trace is sub-vertical to steeply southwest dipping and is made up of a series of sub-parallel fault splays incorporating a fault breccia with blocks of pebble conglomerate and sandstone.

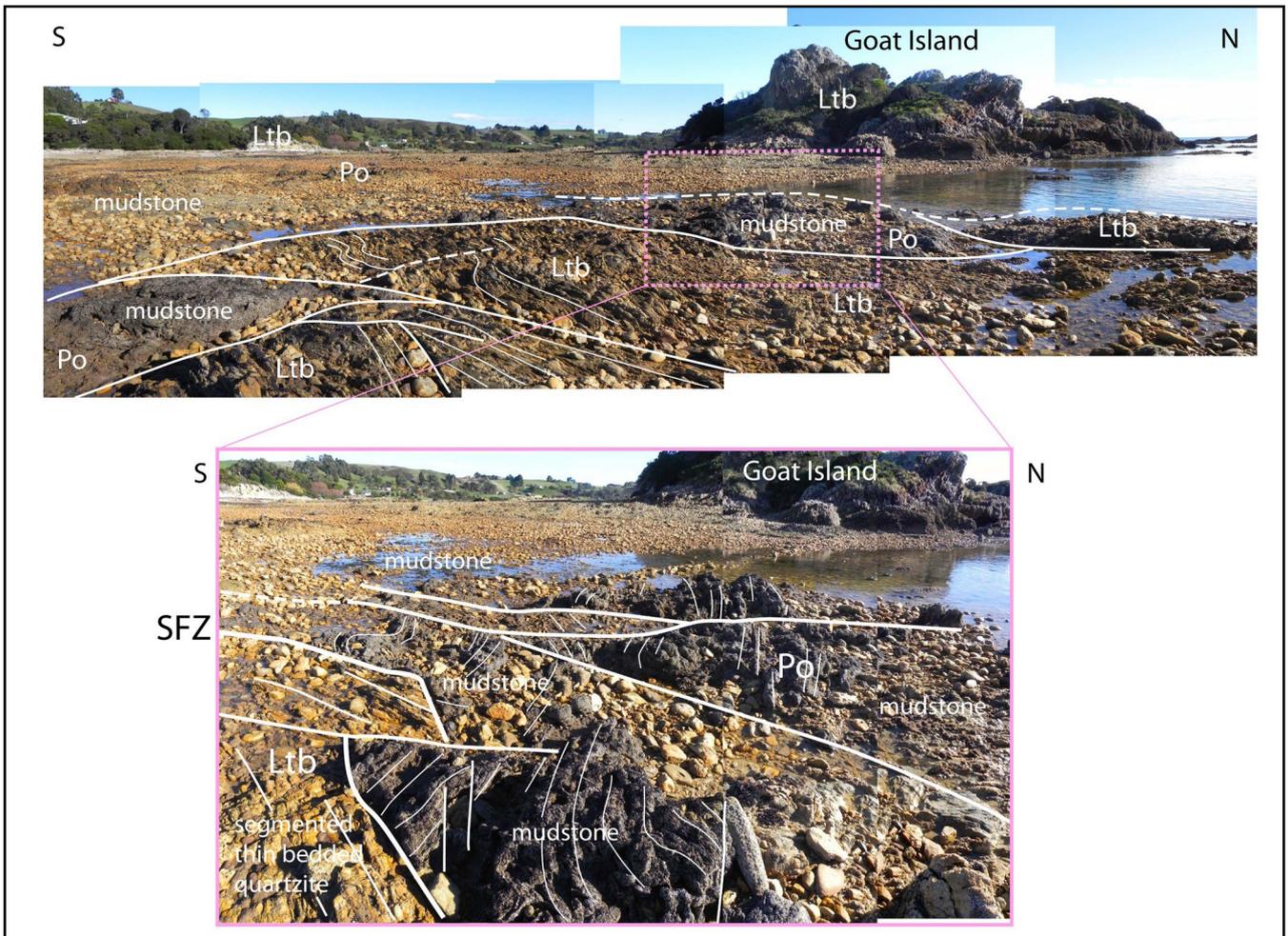
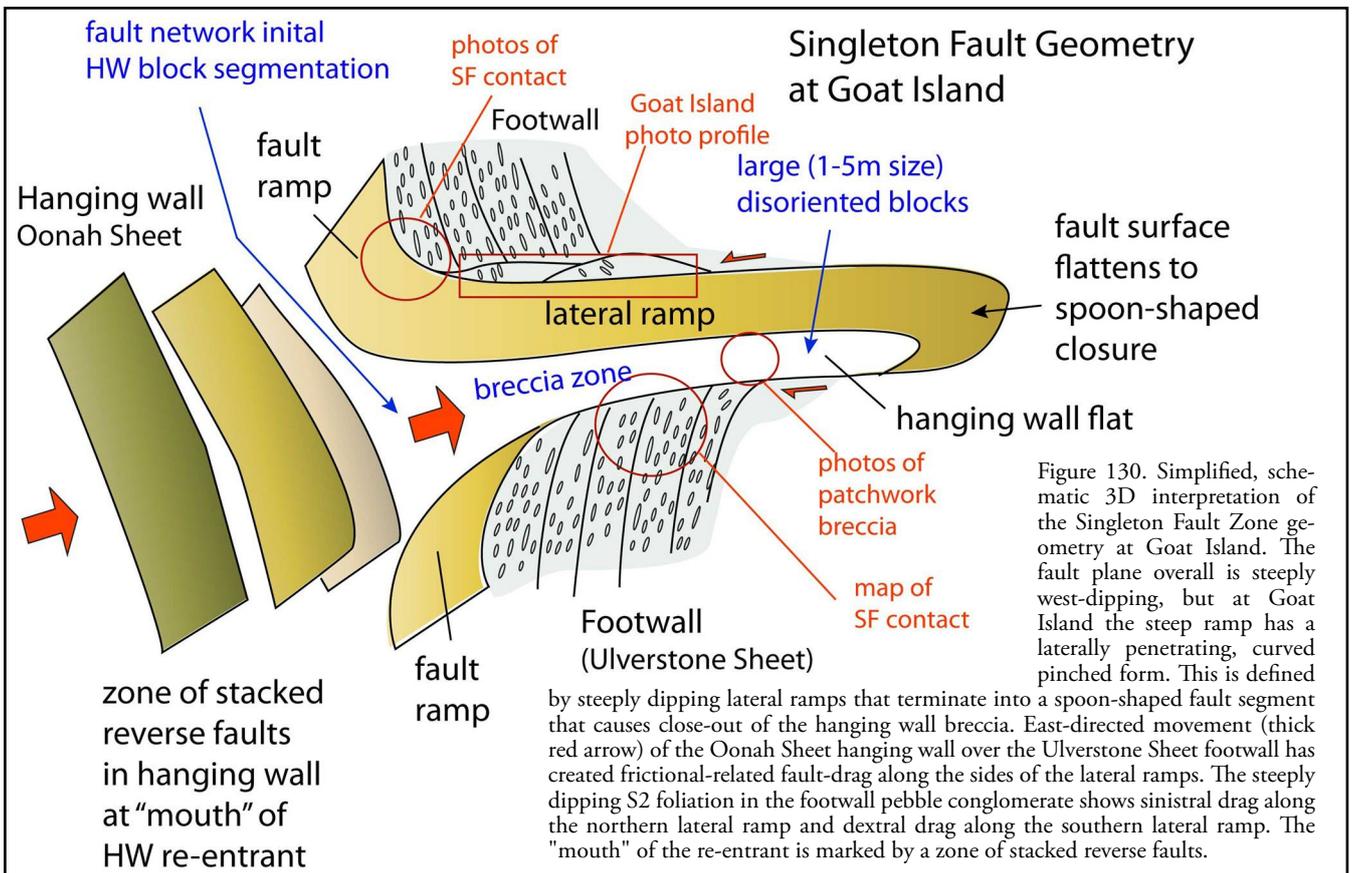


Figure 129. Rock platform east of Goat Island within the Singleton Fault Zone. Steeply fault-bounded, hanging wall-derived, mudstone fragments of the Oonah Sheet are juxtaposed against footwall-derived, fragments of pebble conglomerate of the Ulverstone Metamorphic Sheet. The outcrop is along the southeastern margin of the Oonah Sheet fault-bounded, tongue-like projection "into" the Ulverstone Sheet. The blocks are within the immediate hanging wall to the Singleton Fault.



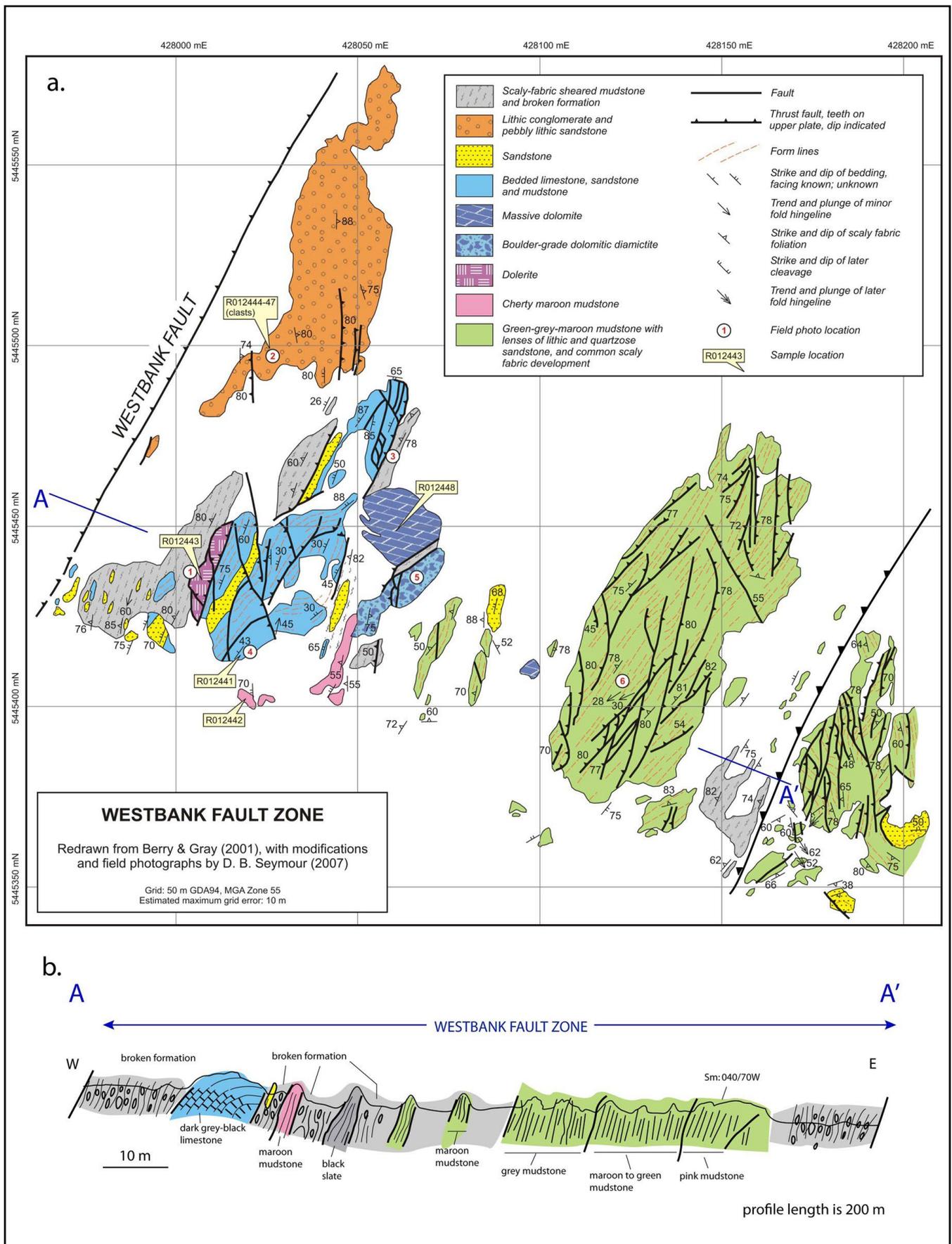


Figure 131. The Westbank fault Zone. a) Structural lithological map of the Westbank Fault Zone modified from Seymour and Vicary (2010) after Berry and Gray (2001). b) Sketch structural profile across the Westbank Fault Zone.

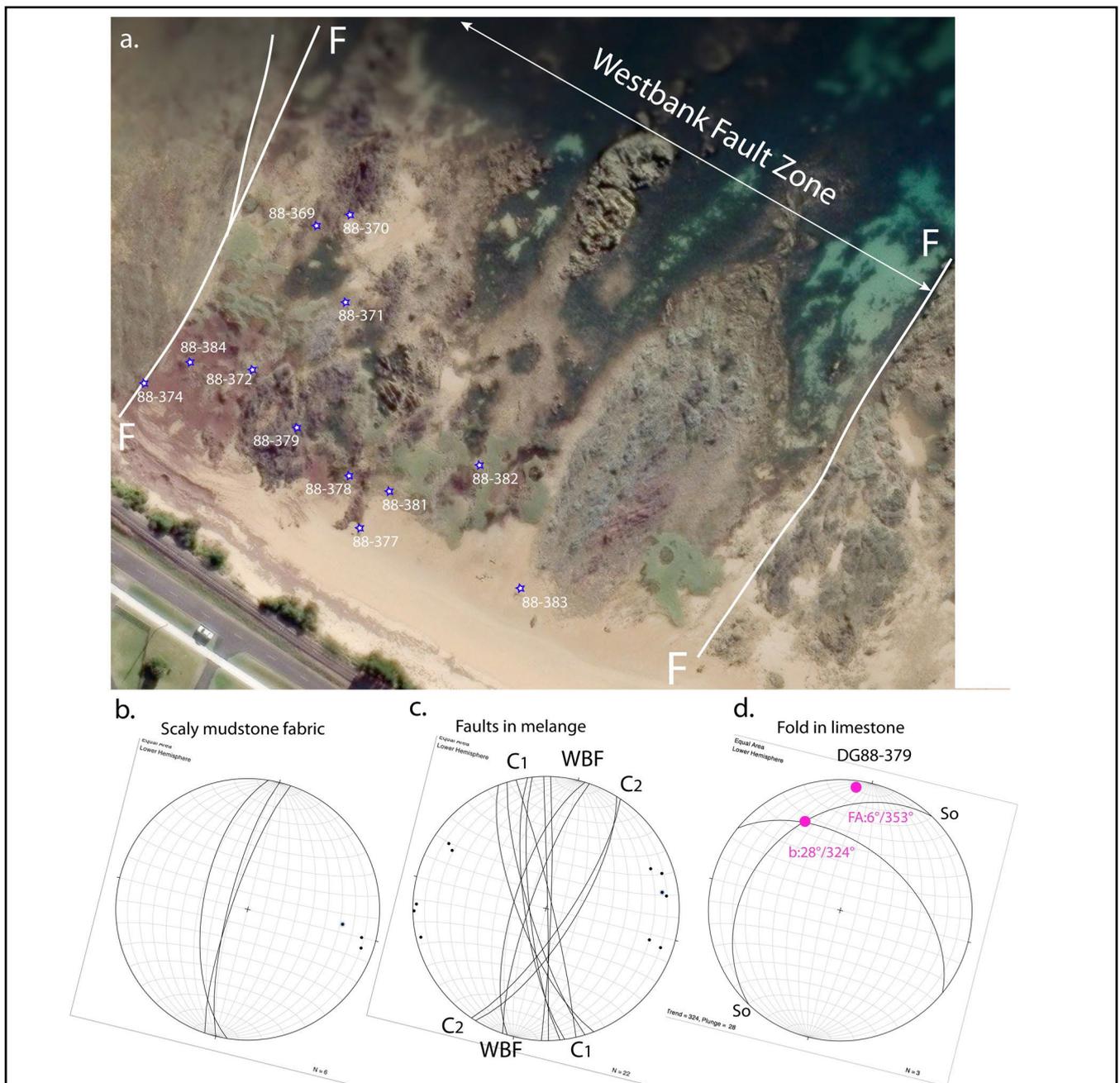


Figure 132. The Westbank Fault Zone DG field stations and structural data. a) Google satellite image of the Westbank fault Zone showing the variously coloured blocks and slabs of different lithologies including black limestone (dolostone), lithic sandstone, pebble conglomerate, dolerite, black shale, and maroon and green mudstone.

The larger slabs of dolostone and sandstone contain open shallowly plunging folds (Figure 132d) whereas the smaller slabs of mudstone have steeply plunging folds which form a girdle parallel to the foliation (Burns, 1964, fig.69). Mélange or broken formation in thin-bedded turbidites adjacent to the Westbank Fault is transitional into scaly fabric in dark grey mudstone (Figures 133, 134 and 135). All mudstone blocks contain a zone-parallel anastomosing cleavage or scaly fabric throughout the fault zone that is steeply west-dipping (Figures 131b and 132b).

The eastern margin of the fault zone was contentious in that Burns (1964) inferred that the breccia was unconformable on Oonah L-G Sheet to the east. However, all lithologic contacts appear to be faults (Figure 131b) and there is no evidence of an unconformity. The recent map-

ping suggests that the eastern boundary to the zone is also a west-dipping fault (Figure 131a and b).

Stereonets of the Westbank Fault Zone structural data show that the:

- scaly mudstone foliation is north-northeast trending and steeply west dipping and is sub-parallel to the faults bounding the Westbank Fault Zone (compare Figure 132b and Figure 132c).
- 3 sets of faults - including 1) a steeply dipping, north-northwest trending set (C1), 2) a steeply east dipping, northeast-trending set (C2), and 3) the north-northeast trending faults defining the Westbank Fault Zone (Figure 132c).
- folds in the large dolostone block (blue in Figure 131a, b) are north and northwest plunging (Figure 132d).



Figure 133. Football-size, sub-rounded, dolostone block within foliated mudstone matrix of the Westbank Fault Zone.



Figure 134. Westbank Fault Zone brecciated mudstone matrix melange. The matrix is composed of mudstone, brecciated mudstone and a black shale fragment all bounded and cut by narrow, brittle faults. The white arrows point to faults and fault contacts. This matrix is host to all the slabs and blocks of different lithologies shown in Figure 131a and 132a).

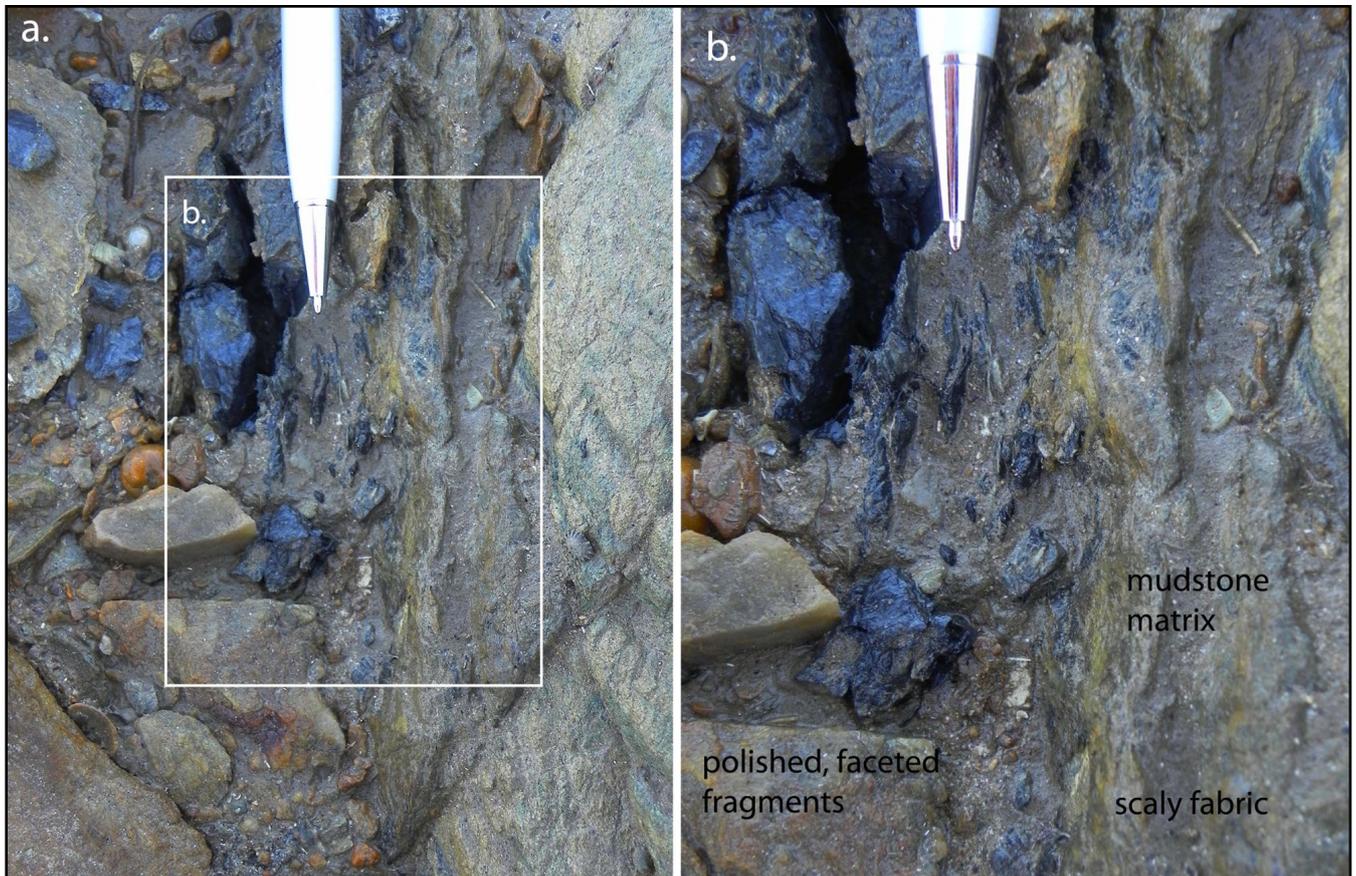


Figure 135. Polished and faceted black carbonaceous mudstone fragments within brecciated scaly mudstone matrix of the Westbank Fault Zone. b) is an enlargement of (a).

#### 4.4.3 Ulverstone Fault Zone

The Ulverstone Fault Zone is an ~400 m wide mélangé zone west of the Picnic Point wave-cut platform (Figure 136). It separates Fault Slice 2 of the West Ulverstone Imbricate Zone (Figure 72) from the underlying Ulverstone Metamorphic Sheet proper (Figures 73 and 74). The fault zone consists of a series of scattered blocks of black mudstone, dolostone, sandstone/quartzite, khaki and green phyllite, siltstone and mudstone all within a scaly-mudstone matrix mélangé (Figure 137).

Deformed pebble conglomerate and intercalated quartz-mica schist of the Ulverstone Metamorphic Sheet occur on both the hanging wall of the fault to the west and in the footwall to the east (Figure 136). Both measured and interpreted second- and third order faults are part of the Ulverstone Fault Zone (Figures 137 and 139). These faults are predominantly northeast trending with moderate to steep, northwest dips (Figure 139a). Subgroups of 355°, 025°, 035°, 055° and 075° trending faults define an intersecting fault array within the Zone (Figure 139b). This internal fault array is considered to reflect late stage, Devonian reactivation within the Fault Zone subjected to NW-SE compression (Figure 139c).

The western, or structurally highest, part of the fault zone is made up of a ~30-40 m zone dominated by blocks of black shale and dolostone of Neoproterozoic Togari Group correlate (Figures 140, 141 and 142b). The black shale blocks have irregular sizes and shapes, contain a scaly, bedding-parallel cleavage, are internally folded and cut by brittle faults (Figures 141 and 142). The blocks are bounded by faults, contain numerous faults, and are generally aligned sub-parallel to the trace of the Ulverstone Fault (Figure 137). The scaly anastomosing, bedding-parallel cleavage is folded by open, shallowly plunging folds that are commonly truncated by numerous faults internal to the blocks (Figure 142). The blocks are also enclosed by mudstone with a scaly fabric (Figure 141c).

The remainder of the Ulverstone Fault Zone is made up of disoriented and poly-deformed blocks of greenschist facies, Ulverstone Metamorphic Sheet (Figure 137). The greenschist facies blocks are also internally deformed with open folds in bedding, refolded folds and multiple crenulation cleavages (Sc<sub>c</sub>), particularly in pelitic lithologies (Figures 138, 143 and 144).



Figure 136. Georeferenced satellite image of the Ulverstone Fault Zone showing the dispersed outcrop pattern of irregularly shaped and disoriented blocks sandstone and phyllitic mudstone. Second and third order faults within the fault zone are shown by the heavy white line traces. Form lines in bedding are shown by the thin white lines within the blocks and enclosing mudstone matrix. The red rectangle highlights the position of the detailed maps shown in Figure 137a, b.

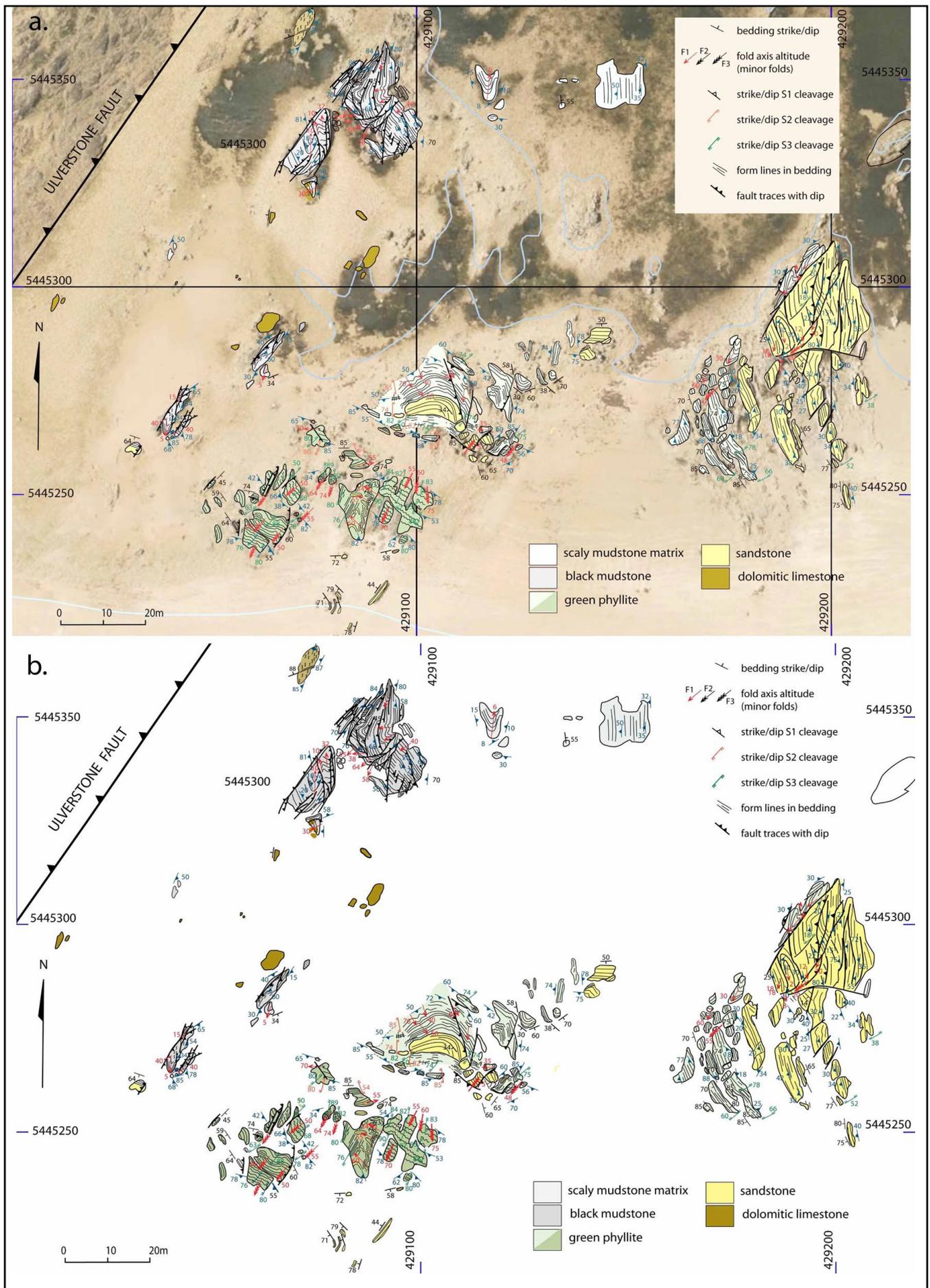


Figure 137. Detailed lithological and structural map of the Ulverstone Fault Zone. The original mapping was done by pace and compass technique but the original map has recently been adjusted and fitted to the georeferenced enlarged satellite photo base shown in (a). b) Structural map of isolated blocks within the Ulverstone Fault Zone. The mapped lithologies are shown in the map legend.

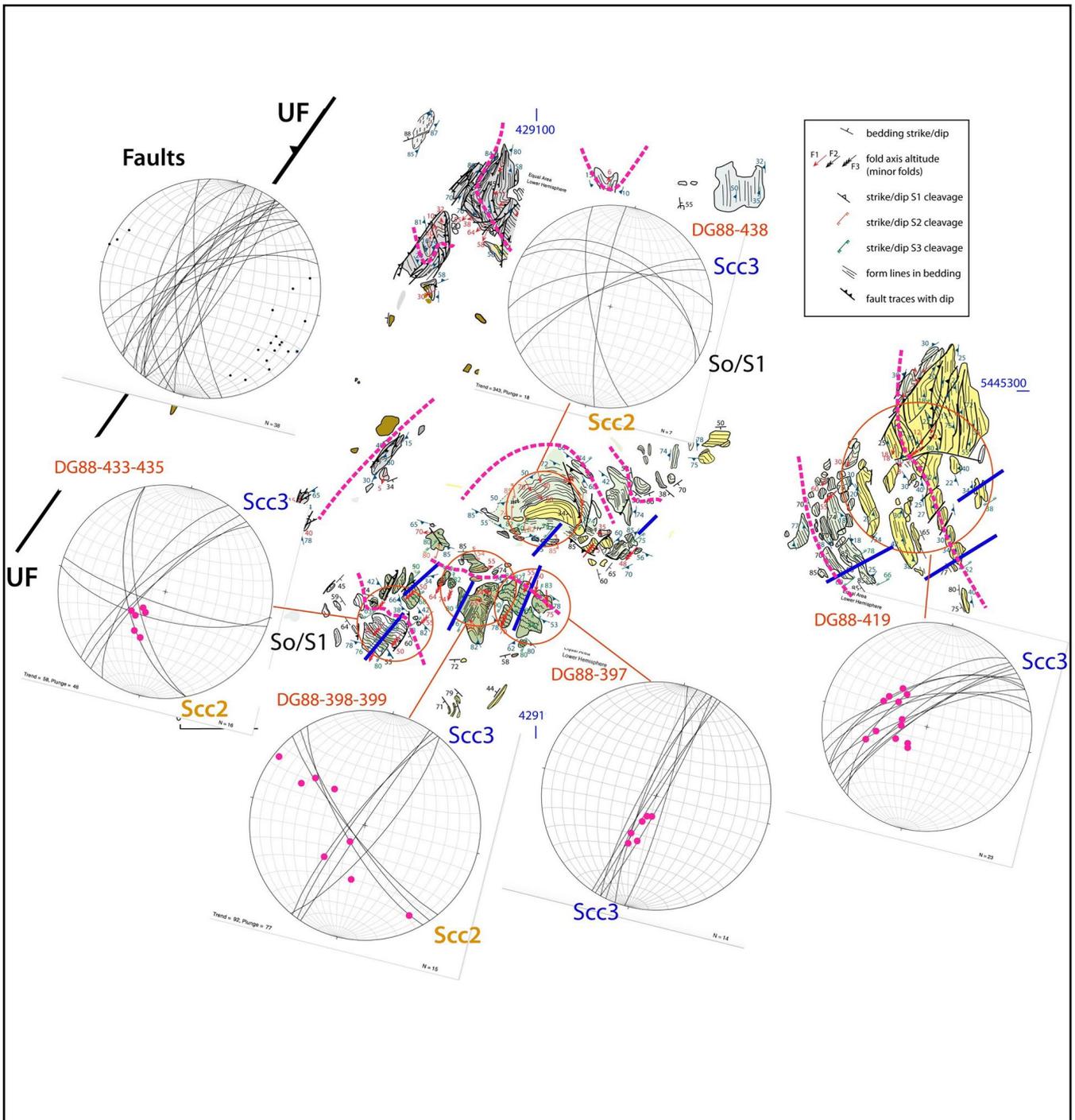


Figure 138. Structural summary map of the southwest corner of the Ulverstone Fault Zone with form lines in bedding So (pink dashed lines), trend lines for the northwest-trending crenulation cleavage Scc2 (orange line traces) and the Northeast-trending crenulation cleavages (Scc3) (blue line traces). Attitudes of the structural elements in the circled areas are shown in stereonet form. Pink dots on the stereonets are fold axis attitudes associated with the designated Scc2 and Scc3 cleavages.

The Fault Zone is dominated by a strong northeast-trending crenulation cleavage associated with southwest-plunging crenulations and mesoscopic folds, particularly in the Ulverstone Metamorphic meta-pelite blocks at the southern end of the zone as it is now exposed (Figure 138). Fold interference patterns and intersecting crenulation cleav-

ages can be seen in some of the blocks, showing that the northeast-trending crenulation cleavage is Scc3 (Figure 138). This crenulation cleavage and the associated folds re-fold an earlier west- to northwest-trending crenulation cleavage designated Scc2 (Figures 137, 138, 143 and 144).

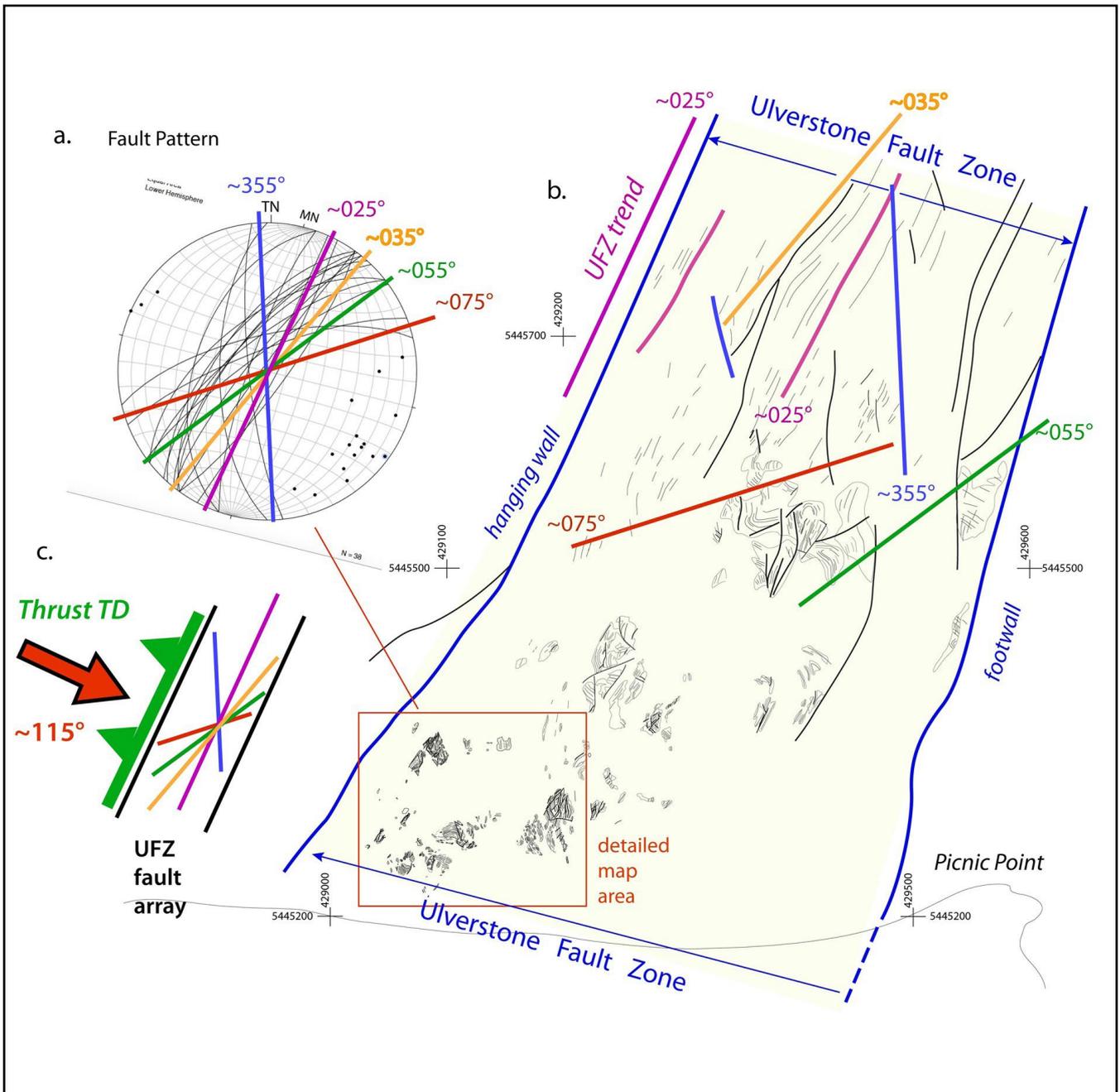


Figure 139. Fault pattern map of second- and third-order faults within the Ulverstone Fault Zone. a) Stereonet of the fault attitudes shown by great circle traces. The fault data are from the detailed map area shown by the red rectangle in (b). Strike groupings are highlighted by the coloured strike traces that can be compared with the line traces on the fault trace map in (b). b) Fault line trace map. c) Interpreted subsidiary fault trace pattern with Devonian transport direction TD (red arrow) bisecting the conjugate subsidiary fault system and approximately orthogonal to the Ulverstone Fault trace.



Figure 140. Wide-angle photograph of the Ulverstone Fault Zone showing the scattered and isolated, irregularly shaped blocks surrounded by sand and pebble detritus. The surficial deposits cover the majority of the fault zone mudstone matrix. The photo is taken from the beach at the southwest corner of the fault zone looking to the northeast. Seagull Islet is on the horizon photo left.

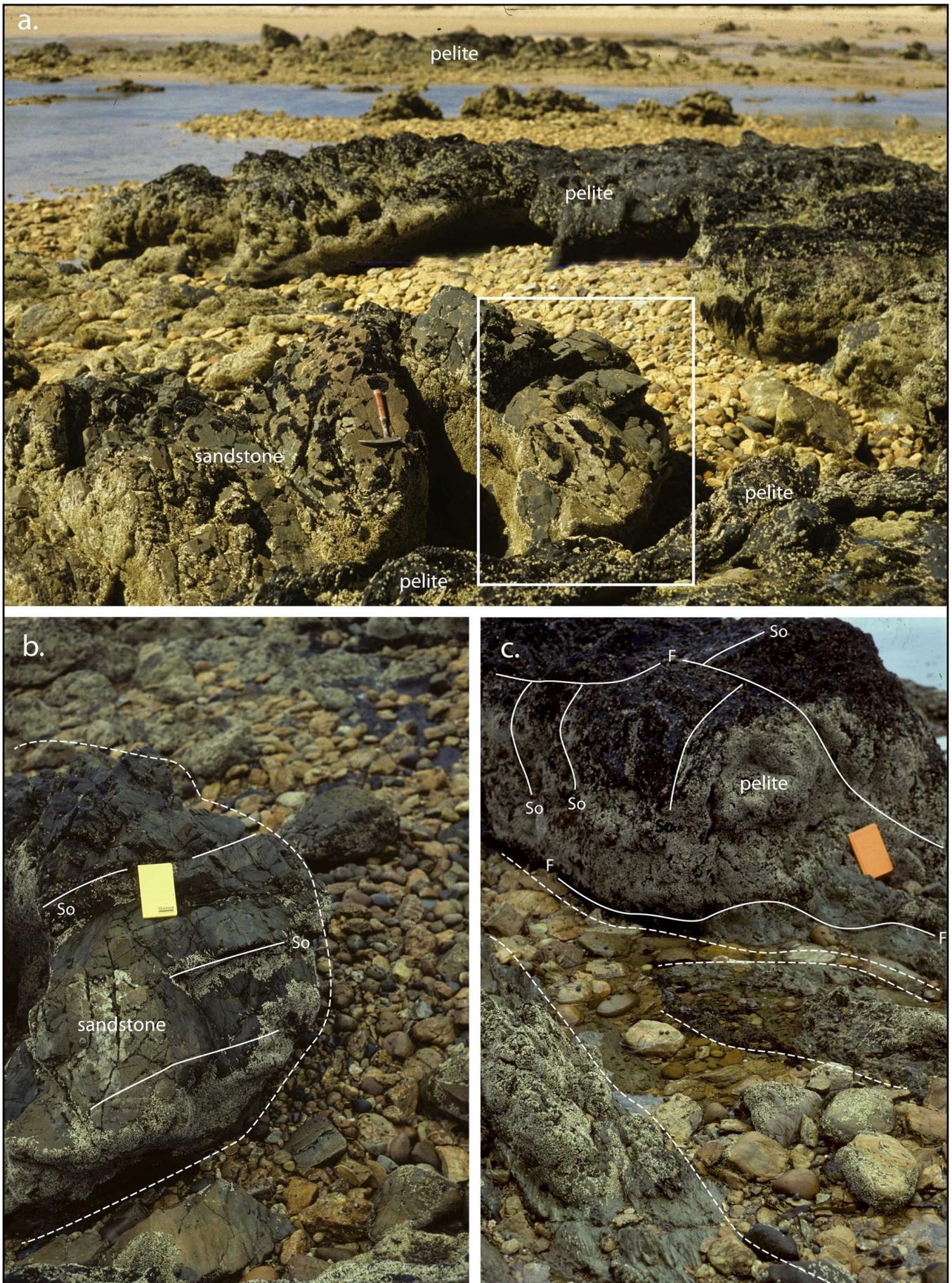


Figure 141. Isolated blocks within the Ulverstone Fault Zone. a) Sandstone block with the bedding (So) truncated at the block boundary. b) Block and slices of silicified black mudstone. The scaly-mudstone matrix supporting the blocks and fragments is covered by pebbles and cobbles.



Figure 142 (Above). The structural character of the black shale blocks along the western part of the Ulverstone Fault Zone. a) and b) show anticlinal folds in a bedding-parallel foliation (So) cut by a slaty-like cleavage (S1).

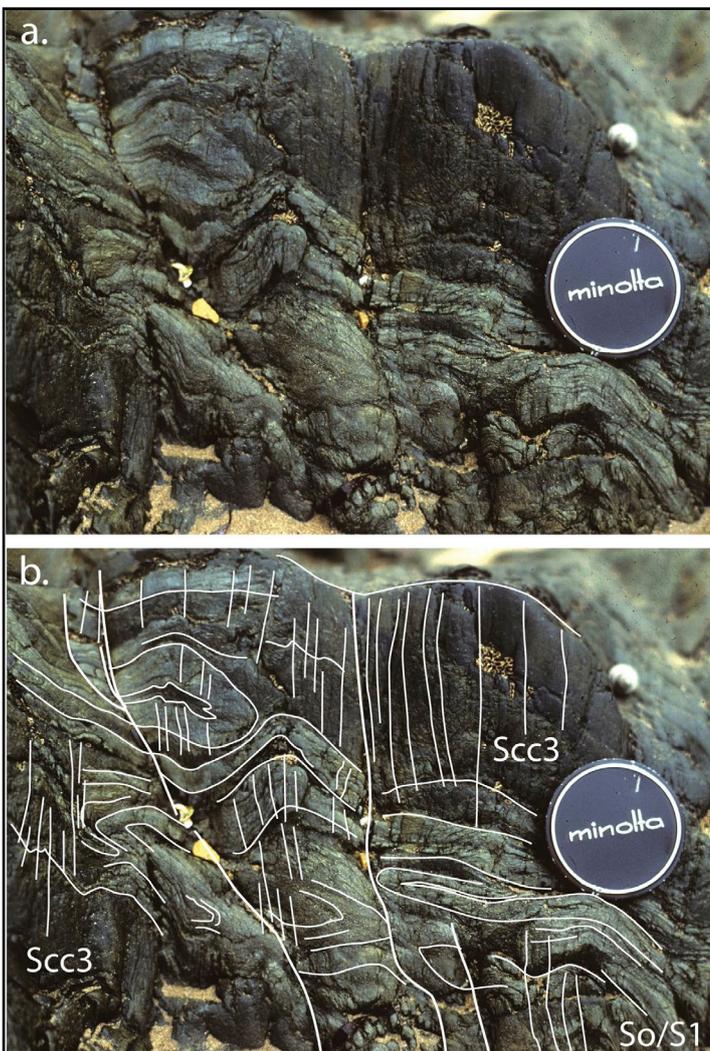


Figure 143 (Left). Early isoclinal folds overprinted by the dominant, northwest-trending Scc3 cleavage (thin white vertical line traces). The microfabric of the bedding-parallel foliation and the overprinting Scc3 cleavage are shown in Figure 145.

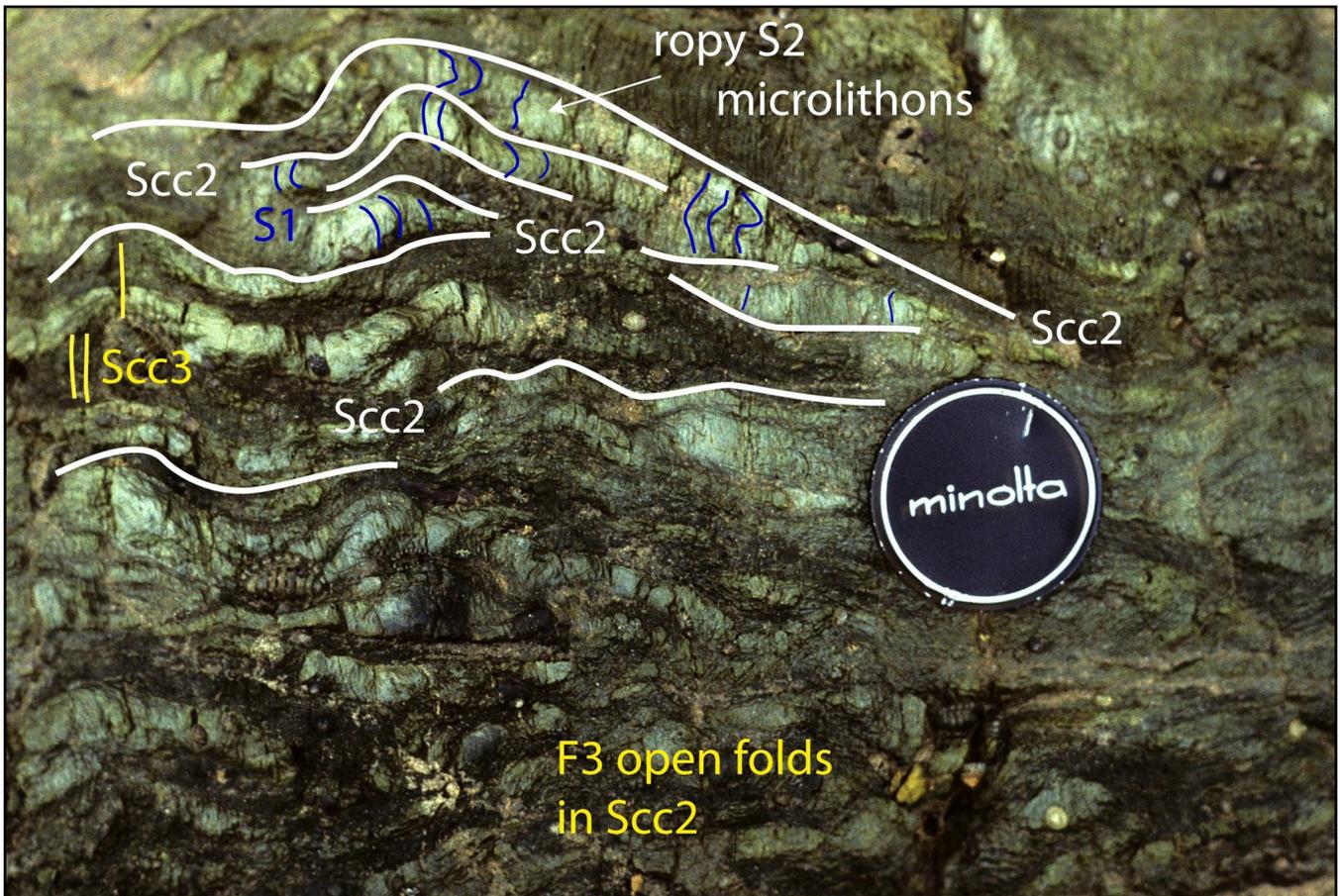


Figure 144. Multiple crenulation cleavages in a phyllitic-pelite block within the Ulverstone Fault Zone (see Figures 137b and 138). An earlier Scc2 fabric (horizontal white line traces in plane of the photograph) is distinguished by broad, cm-scale microlithons that are highlighted by the mica sheen to give a "ropy" appearance. Thin dark, discrete crenulation cleavages Scc3 (vertical yellow line traces) overprint the earlier Scc2 fabric. These are axial surface to the open fold undulations in the ropy Scc2 fabric.

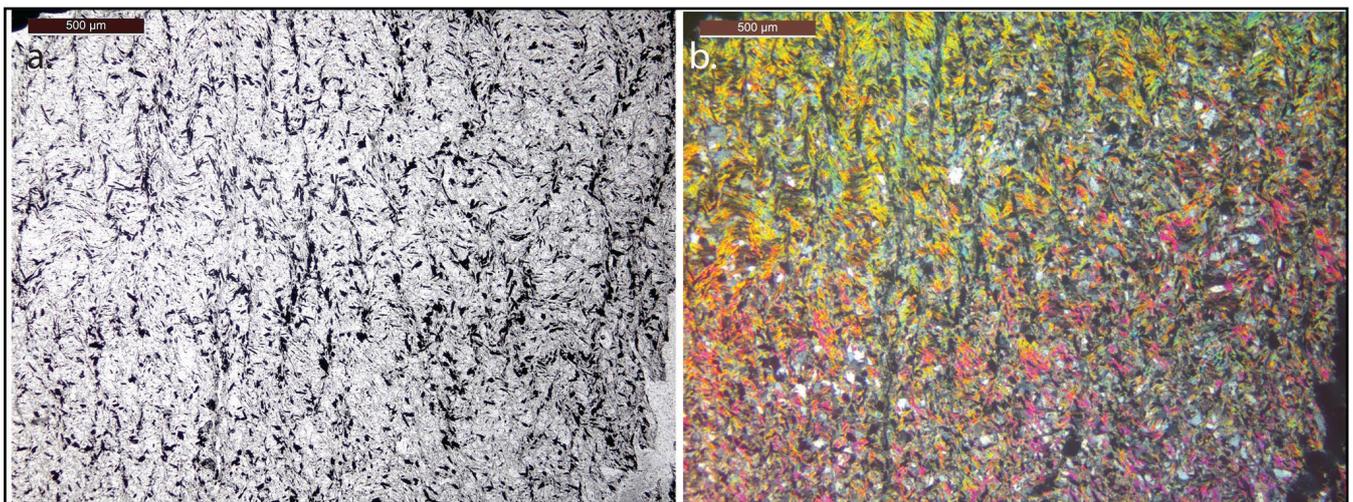


Figure 145. Photomicrographs of crenulation cleavage (Scc3) fabric in poly-deformed pelite block (phyllite) within the Ulverstone Fault Zone (Station DG88-419). a) PPL micrograph. b) X-nicol. The crenulation cleavage is a weak spaced cleavage (vertical) crenulating a bedding-parallel mica fabric (sub-horizontal).

## 5.0 STRUCTURAL IMPLICATIONS OF THE ULVERSTONE METAMORPHIC SHEET AND THE WEST ULVERSTONE IMBRICATE ZONE

### 5.1 Nature of the External Zone-Internal Zone interface

Berry (2014) introduced the concept of External and Internal Zones for the Tasmanian Cambrian subduction-exhumation-obduction system based on analogy with the structural metamorphic-architecture of ophiolite obduction in arc-continental collisional settings in Oman and the New Foundland Appalachians. The interface is equivalent to the Upper Plate-Lower Plate discontinuity in the Saih Hatat Window in Oman (see Miller et al., 1998; Gray et al. 2005), where low grade, parautochthonous sedimentary rocks sit above and in fault contact with metamorphic sheets incorporating blueschist and eclogite.

By definition, the External Zone consists of ophiolite overlying very low- to very low-grade shelf sequences. In Tasmania it consists of variably deformed and metamorphosed Neoproterozoic Oonah sandstone-mudstone sequences (Holm and Berry, 2002), with the highest metamorphic grade (blueschist facies) seen along the western margin of the zone (Everard, 1999; Turner and Bottrill, 2001). The blueschists occur at the base and apparent leading edge of the sheet. The Internal Zone consists of a complex structural sequence of strongly folded and metamorphosed sedimentary rocks in an obduction/exhumation sheet stack, equivalent to the metamorphic regions such as Saih Hatat in Oman (Miller et al., 1998). In Tasmania it includes the prominent Tyennan Domain occupying central Tasmania south of the Dundas-Fossey Graben (Gray et al., 2023) and the H-G Forth Metamorphic Sheet north of the Dundas-Fossey Graben.

The External Zone-Internal Zone contact in northern Tasmania is not fully exposed. The actual interface between the H-G Forth Metamorphic Sheet (Internal Zone) and the L-G Ulverstone Metamorphic Sheet (External Zone) is most likely a foliation Sm/parallel strain transition, as suggested by the East Ulverstone platform exposures (Figures 106 and 117). The other issue is that most of the contacts between the L-G sheets and the H-G sheets have been fault-reactivated during younger Devonian deformation (see Section 5.5).

The External Zone is made up of the sub-greenschist L-G Oonah Sheet and a greenschist, high strain Ulverstone Metamorphic Sheet distinct from the underlying H-G Forth Metamorphic Sheet (Internal Zone). These are overlain by the Cambrian Luina Sheet, consisting of chert and oceanic tholeiitic basalt, and the Cambrian ophiolite now preserved as erosional remnants of a once contiguous ultramafic sheet. The interface between the Oonah L-G sheet and the Ulverstone Sheet can be seen at two locations, including 1) the West Ulverstone Beach, and 2) the Picketts Road cutting (see star localities, Figure 72).

The west Ulverstone beach exposure shows an interface between sub-greenschist, L-G Oonah Sheet and greenschist facies, L-G Ulverstone Sheet, without significant Devonian fault reactivation (Figure 146). The contact is a foliation-parallel interface where Sm in the quartzite/conglomerate of the Ulverstone Sheet is subparallel to Sm (S2) in the folded, low-grade sandstone-pelite of the Oonah Sheet. The sub-greenschist facies Oonah Formation mudstone-sandstone is "welded" to part of the Ulverstone Metamorphic Sheet as a foliation-parallel strain transition (Figure 146). This strain transition should be typical/representative of contacts between sheets at the deeper levels of the obduction stack, whereas at shallower levels brittle faulting and mélangé occupy the contacts.

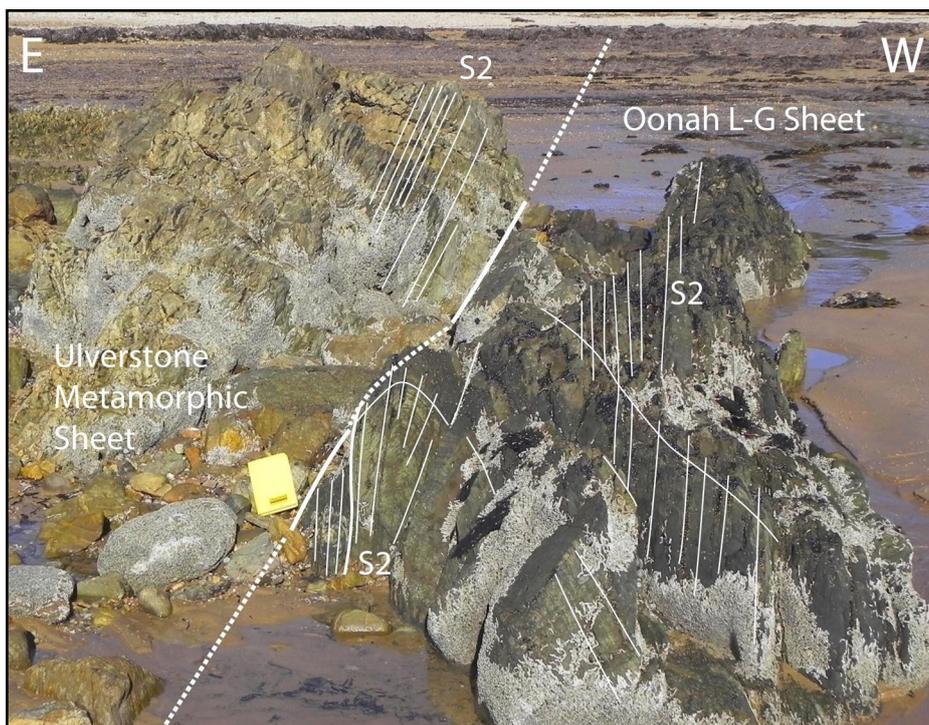


Figure 146. Deformed, apparent "welded" contact between the Oonah L-G slice (sub-greenschist mudstone and interbedded sandstone sequence) on the west (photo right) and the deformed, greenschist facies, pebble conglomerate/quartzite sequence on the east (photo left). The contact is sub-parallel to the dominant foliation (S2) in both the Ulverstone and Oonah Sheets. There is no apparent evidence of a faulted contact.

The Picketts Road locality shows a faulted interface between greenschist facies, polydeformed quartzite-schistose phyllite sequence and the low-grade, sub-greenschist Oonah sandstone-mudstone sequence (Figure 147). The base of the Oonah Sheet and the interface is a zone of steeply, overall east-dipping, undulating sub-parallel faults. A se-

ries of steeply plunging asymmetric folds with an axial surface crenulation cleavage are associated with the faulting in the Oonah Sheet (Figure 147). Kinematic analysis of rare slickensides on one of the faults indicates N-over-S reverse fault movement, with little or no Devonian east-directed fault reactivation (Figure 148).

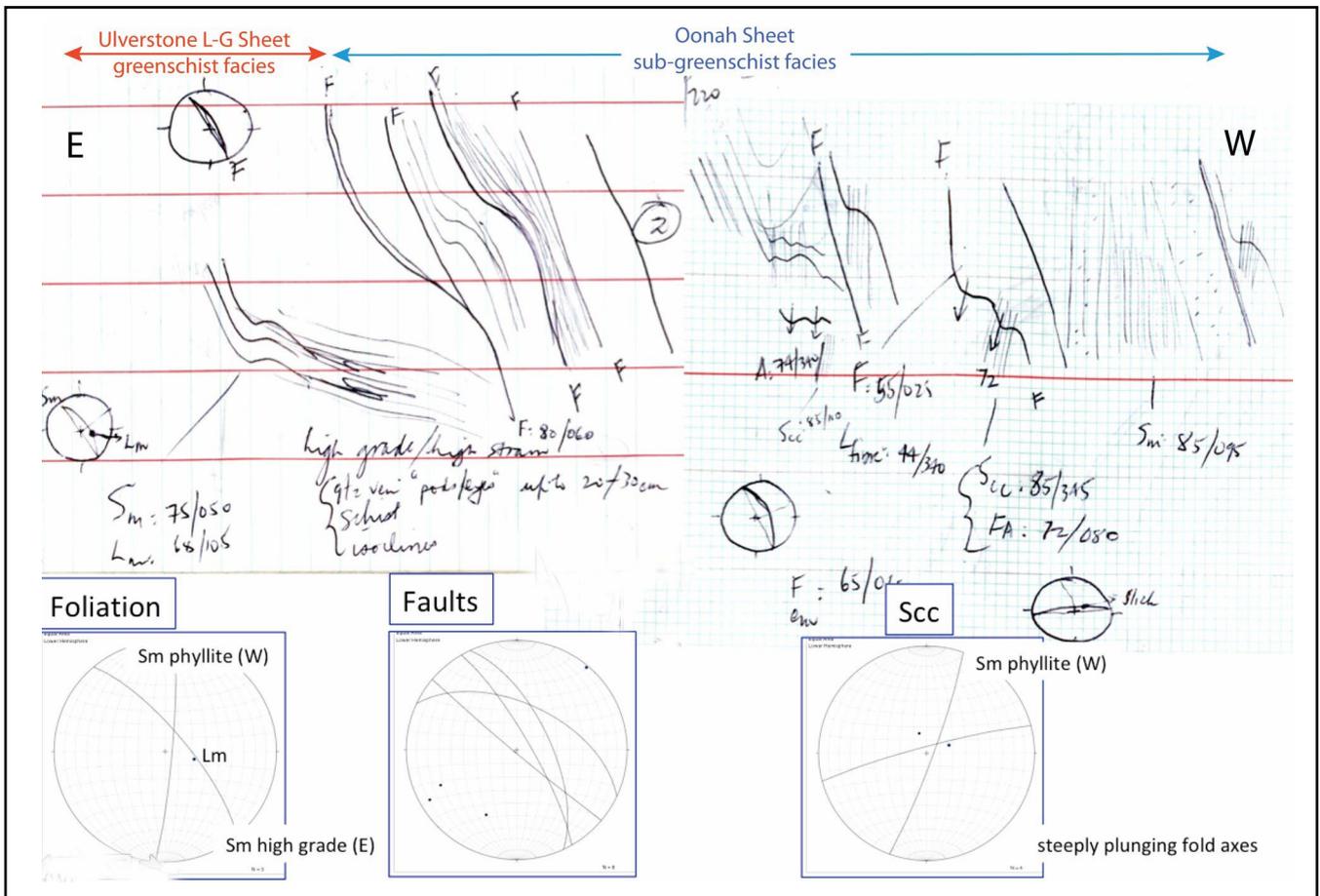


Figure 147. Sketch profile across the Picketts Road HSZ. Note the cutting is slightly oblique to the measured structural trends giving apparent dip traces in the cutting/sketch profile. The greenschist facies Ulverstone Metamorphic Sheet is on the east and the sub-greenschist facies Oonah Sheet on the west. All dips are to the east or northeast as shown in the stereonets.

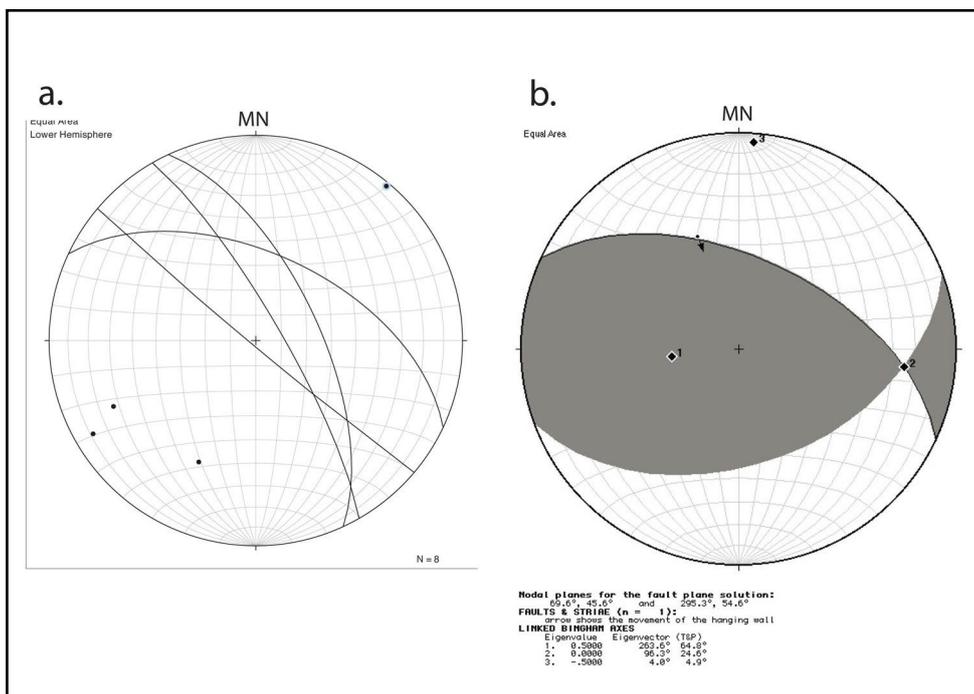


Figure 148 (Left). Stereonets of the fault population in the Picketts Rd. HSZ. a) Great circle traces of faults showing steep to moderate northeast dip. b) Faultkin analysis of fault [55/025 or 295/55 NE with Lslic: 44/340 magnetic]. The calculated thrust vector is towards 184° (magnetic) or -200° TN.

## 5.2 Strain Transitions Between and Within Sheets

The structural character, the significant differences in metamorphism, the strain heterogeneity and strain transitions between and within sheets is shown in a schematic summary diagram (Figure 149).

The Oonah L-G Sheet is preserved within Fault Slices 1 and 2 that make up the West Ulverstone Imbricate Zone (Figures 73 and 74). The sub-greenschist facies sandstone/mudstone sequence, particularly within the West Ulverstone beach slice (Fault Slice 2) is internally folded by upright-horizontal folds. These folds have overall steeply west-dipping axial surfaces and associated S2 cleavage with moderate to gently plunging fold axes (see Section 4.2.2). Within the slice there is no apparent variation in strain (see Figure 74). The Westbank Siding slice (Fault Slice 1) is largely homoclinal west-dipping although poly-deformed and folded within some fault-bounded panels as part of the Devonian fault stack in the hanging wall to the Singleton Fault. Broken formation and mélangé zones occur at the base of the Oonah L-G sheet and at the base of the Ulverstone L-G Sheet, preserved within the Devonian reactivated Westbank and Ulverstone Fault Zones (see Figures 73 and 74).

The Ulverstone Metamorphic Sheet is strongly to intensely deformed and shows significant strain throughout (Figure 149). This is characterised by intense transposition foliation, schistose to mylonitic zones and shear lozenge augen at all scales (see Section 5.3). Folds tend to be asymmetric S-vergent fold pairs many within shear lozenges (Figures 150 and 151).

In contrast the lowermost Forth H-G Metamorphic Sheet shows significant strain variation from the top to the bottom of the sheet with a change from a spaced crenulation cleavage (Scc2) to a strong schistosity towards the base of the sheet (Gray and Vicary, 2026). Within the sheet, high strain domains are characterised by mylonite zones associated with zones of steeply plunging folds, many with curved hinge lines with varying plunge within the dominant foliation Sm (Figure 150b).

## 5.3 Shear Lozenge Development- A Scale Invariant Deformation Process

The coastal exposures of the Ulverstone Metamorphic Sheet provide a comprehensive structural definition of a suite of siliclastic rocks that have undergone extreme simple/general shear strain. There is marked heterogeneity of strain with development of schistose and mylonitic zones that incorporate shear lozenges (pods or augens) at all scales. The pods either develop from asymmetric fold pairs (Type 1 Augen, Figure 151) or as large scale shear band lozenges (Type 2 Augen, Figure 151). The Type 1 asymmetric fold augen include metre-scale augen (Figure 152) to the Picnic Point Shear lozenge at ~115 m length scale to the Seagull Islet macro-shear lozenge at ~620 m length scale and (Figure 153).

## 5.4 Sheet Emplacement Indicators and Markers—Transport Direction and Sheet Kinematics

Riedel shear elements formed in general shear deformation include brittle (faults) and ductile (shear band) components. The attitudes and relationships of these elements can be used to establish the overall emplacement sense and deformation kinematics within a fault- and/or shear zone bounded sheet during emplacement. These markers are presented and discussed with respect to emplacement of the Ulverstone Metamorphic Sheet and the Forth H-G Sheet.

### 5.4.1 Stretching Lineation

The presence of a prominent stretching lineation developed in a simple or general shear deformation can be used to define the movement plane for that deformation (Figure 154a). Other criteria are needed to define the sense of shear within the movement plane.

Movement plane MP1 data from the Seagull Islet-Picnic Point quartzites show a predominantly south-southwest/north-northeast strike (Figures 46 and 154c). The MP1 movement planes strikes spread over ~30° interval between 220° and 190° with a vector mean of ~204° (n=3) (Figure 154c).

### 5.4.2 Shear Bands

Shear bands provide a definitive shear sense in generalised or simple shear within rocks undergoing ductile deformation (Figure 155a and b). They are relatively common in the Ulverstone Metamorphic Sheet and show an overall sinistral or north-over-south shear sense (Figures 156 and 157). The restored transport directions from shear bands are shown in Figure 157. There is a spread from 190° to 140° with a vector mean of ~170° (n=5) (Figure 157).

### 5.4.3 Crenulation Cleavage

Crenulation cleavage (Scc) fabrics reflect a generalised shortening direction within a foliated rock mass. In the West Ulverstone Imbricate Zone from Westbank Siding to Picnic Point there are two sets of crenulation cleavages suggestive of two shortening events (Figure 158). These are:

1. Scc1 with NW-strike and generally with NE-dip reflecting a NNE-SSW shortening component during the north- over-south sheet transport/emplacement. The overall shortening direction vector mean is ~230° (n=4)
2. Scc2 with NE-strike and generally with NW-dip reflecting a within-sheet NW-SE shortening during the younger Devonian thrusting and development of the West Ulverstone Imbricate Zone (push to the east). The overall shortening direction vector mean is ~138° (n=3)

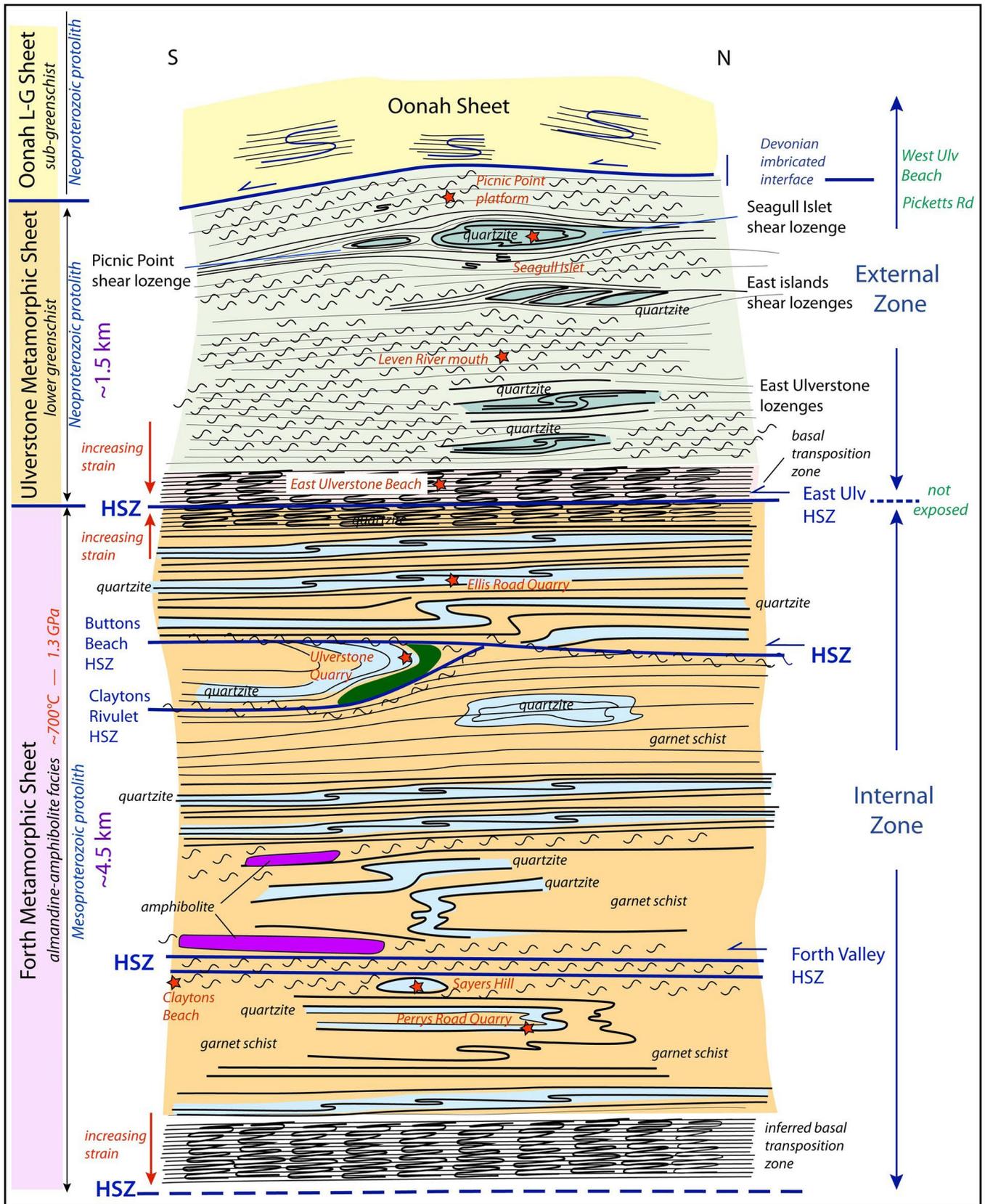


Figure 149. Restored, schematic pre-Devonian subduction-exhumation stack for the Forth-Ulverstone area. The sheet stack consists of the uppermost or structurally highest Oonah L-G Sheet, overlying the ~1.5 km thick Ulverstone Metamorphic Sheet, overlying the ~4 km thick Forth H-G Metamorphic Sheet. The geometry and structural positions are constructed using the up-plunge projection diagram (figs. 14 and 15, Gray and Vicary, 2026).

Orange: H-G garnet schist lithology. Light Blue: quartzite. Purple: amphibolite. Green: serpentinite. Teal: L-G intensely foliated, intercalated schistose quartzite, quartz-mica schist and phyllite. Yellow: sub-greenschist facies sandstone-mudstone sequence. HSZ: High strain zone. The red stars indicate the approximate positions of geographic locations.

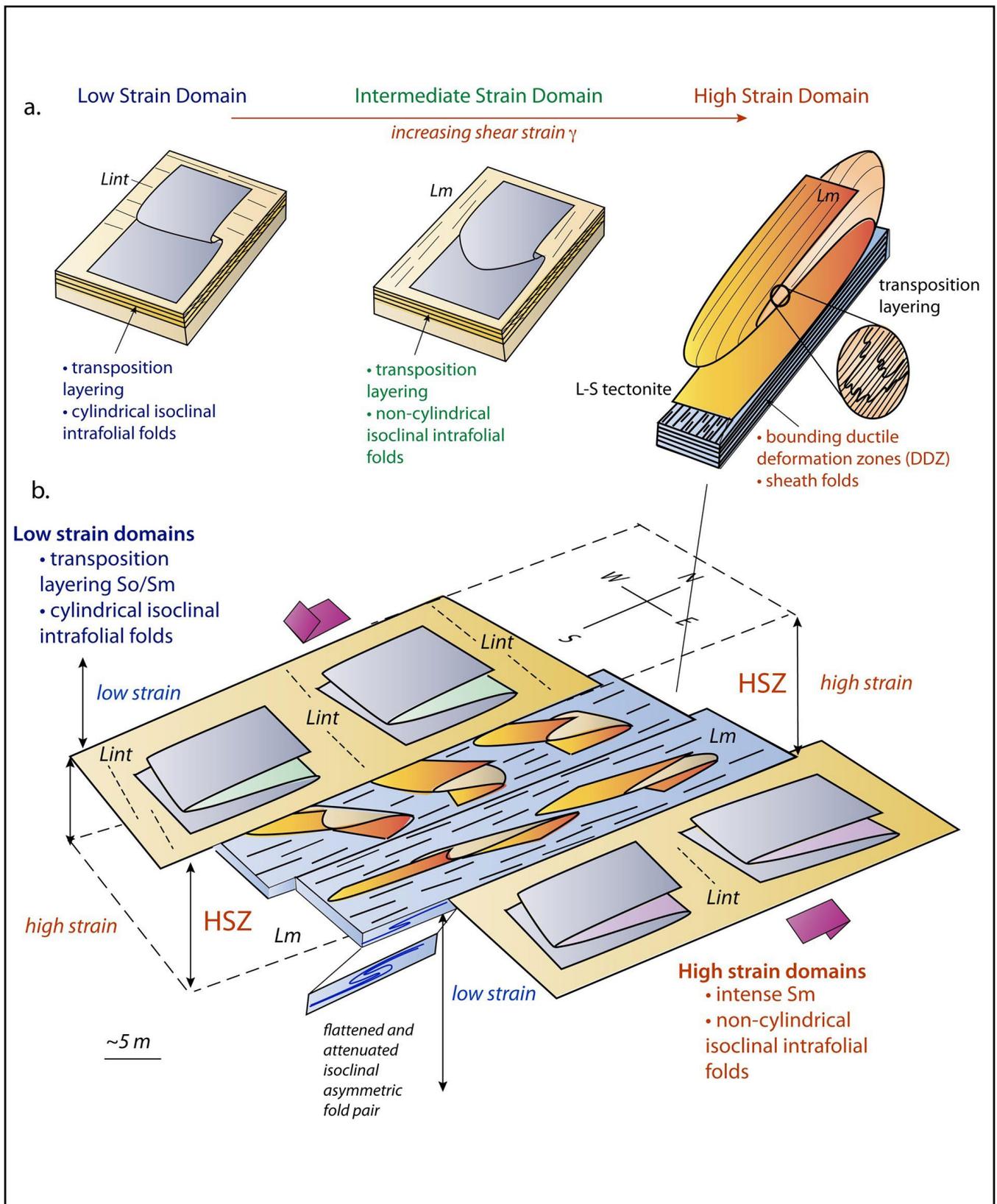


Figure 150. Schematic geometric model of strain transitions in the Forth H-G Metamorphic Sheet.

1. Fold shape changes with increasing shear strain from cylindrical to highly non-cylindrical folds developing marked curved hinge lines.
2. Strain transition diagram from alternating low and high strain domains within the Forth Metamorphic Sheet.

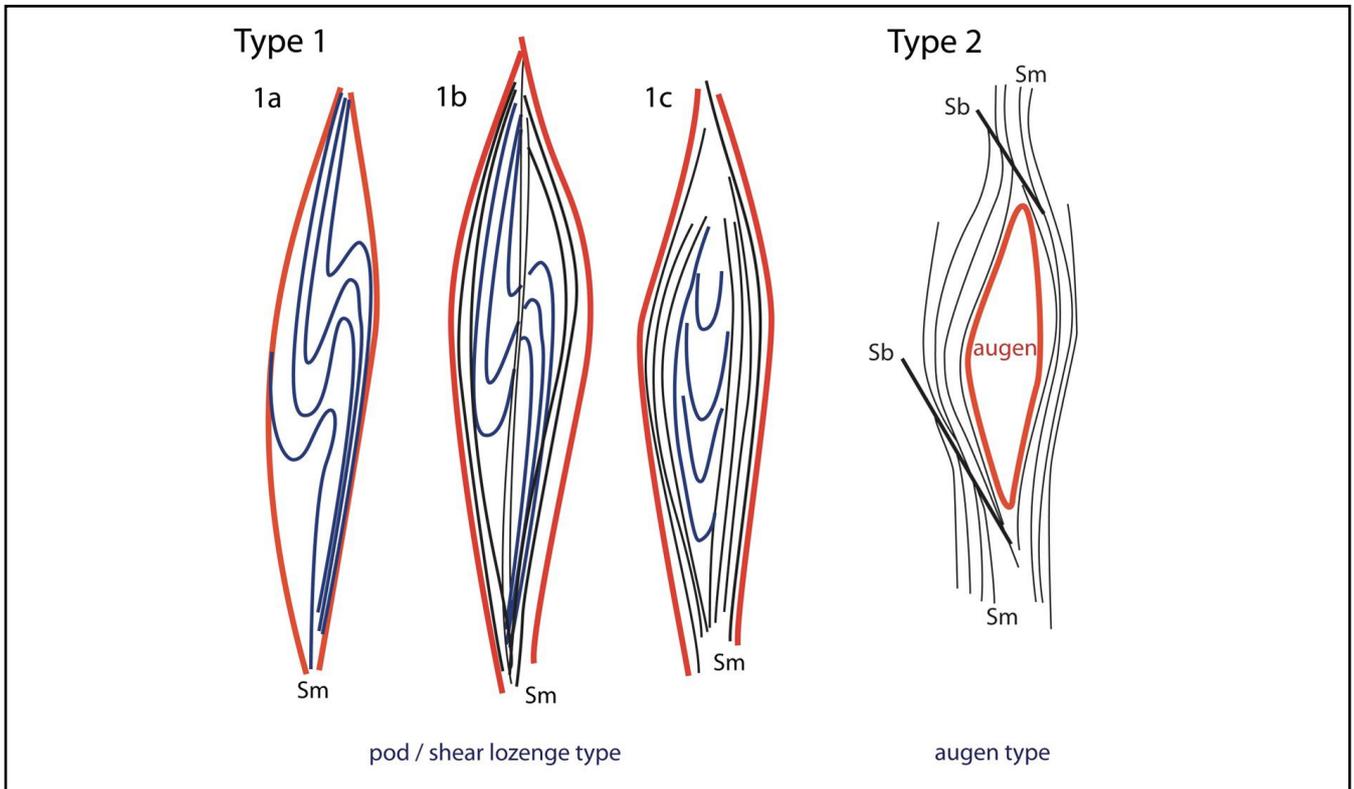


Figure 151. Schematic evolution diagrams of augen or pod development within a high strain zone.

**Mechanism 1:** Augen evolution from an symmetric fold couple enveloped by a dominant transposition layering. Stages 1a to 1c show mylonitic, high strain zone cannibilsation of the initial fold pair (1a) to a segmented or decoupled fold pair (1b) to an isolated fold hinge (1c).

**Mechanism 2:** Augen evolution from shear band development with isolation and preservation of a shear band lozenge. Note the different internal character of augen formed by Mechanism 1 versus Mechanism 2. Mechanism 1 preserves either as fold couple or a single hinge, whereas Mechanism 2 preserves a sigmoidal foliation.

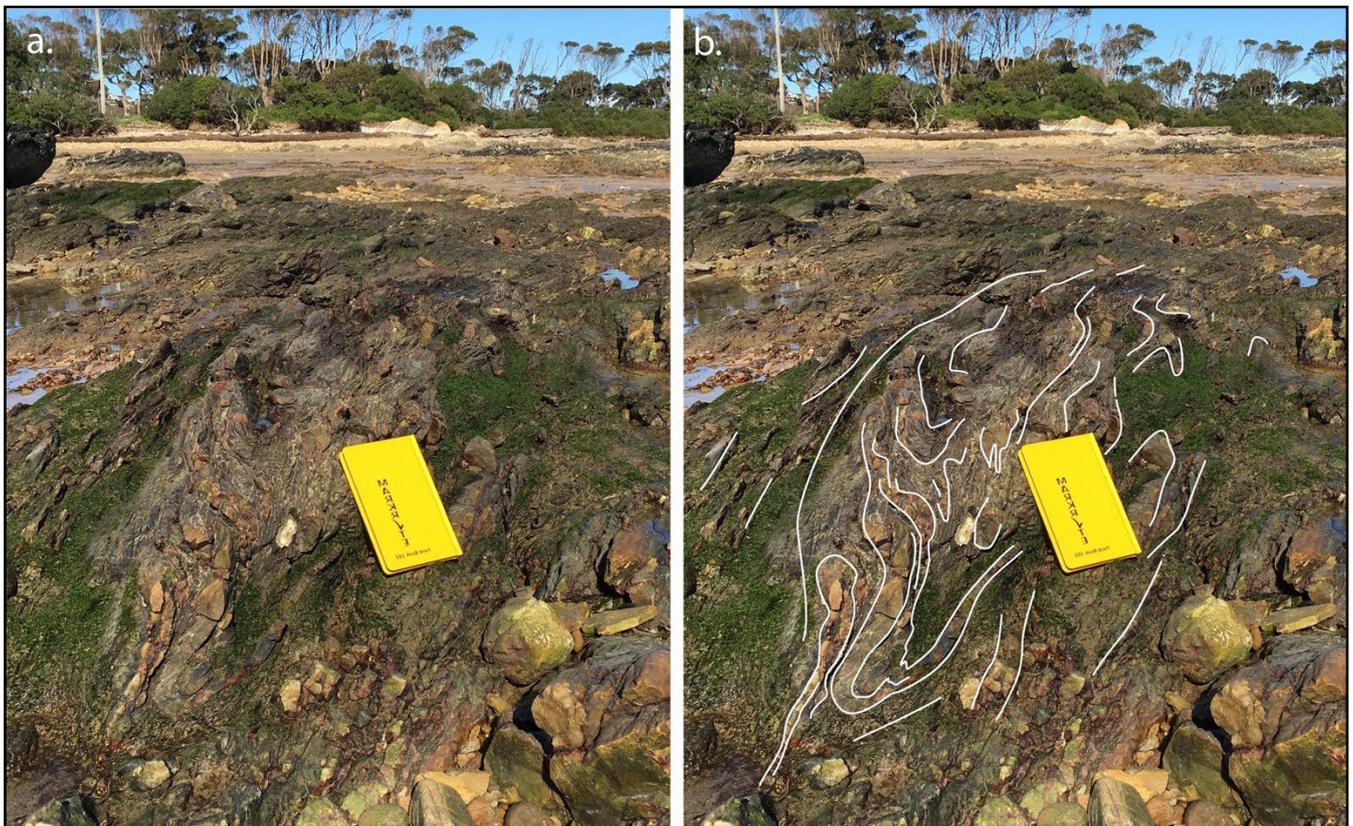


Figure 152. A metre-scale shear lozenge within intensely deformed, high strain fabrics beneath, or east of, the intermediate-scale Picnic Point Shear lozenge. The lozenge shows folded, disrupted and segmented thin-bedded quartzite layering enveloped by the intense Sm foliation. The overall fold form within the lozenge is a synformal closure. This an example of the scale-invariant deformation processes involved in sheet emplacement of the Ulverstone Metamorphic Sheet. Note the photo is inverted to match the geometry shown in Figure 153 below.

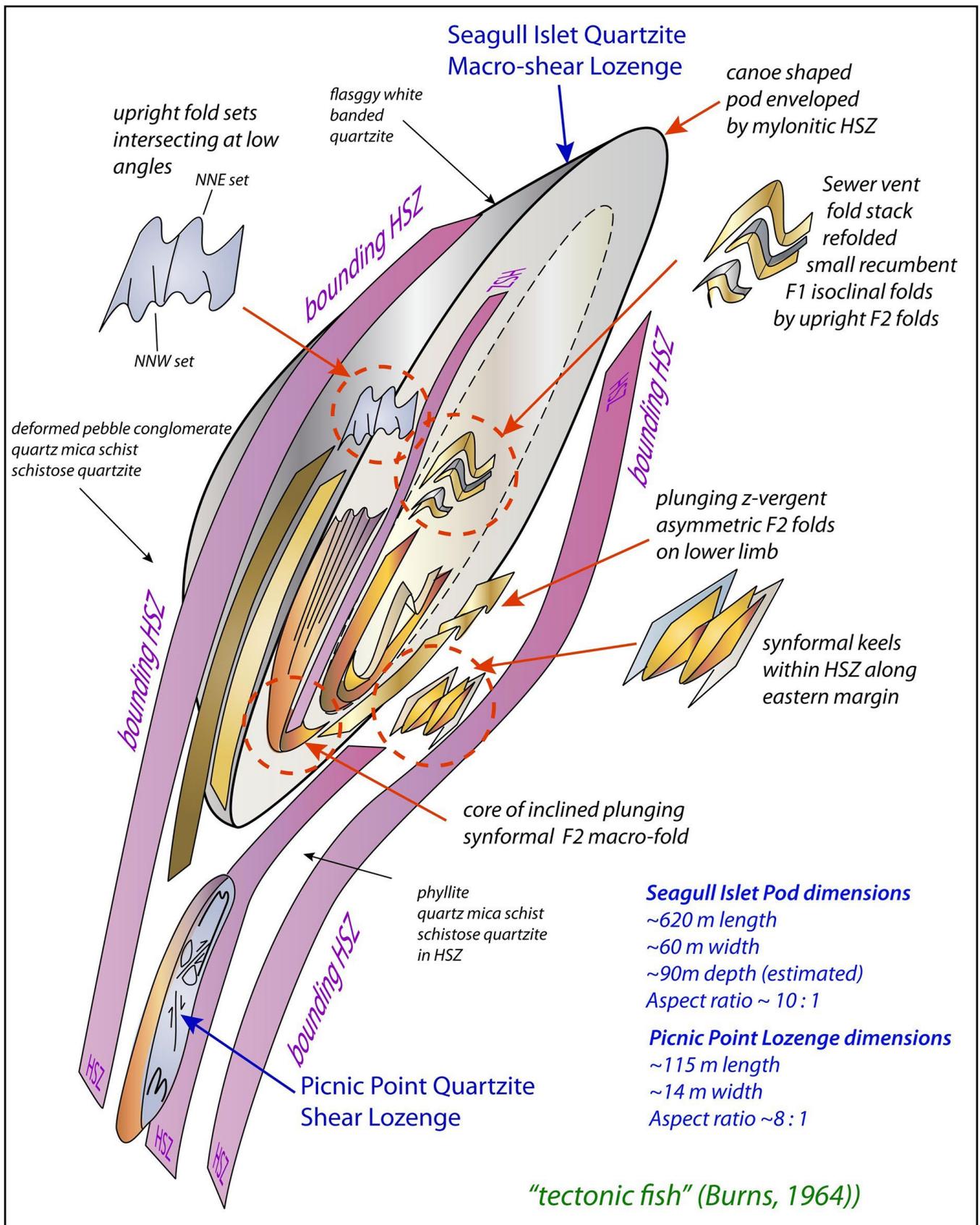


Figure 153. Schematic summary diagram of the form, character and internal structure of the Seagull Islet and Picnic Point Shear lozenges. These are the "tectonic fish" of Burns (1964). The Seagull Islet lozenge has a ~620 m length scale (X), a 58 m width (Z) and an estimated 90 m depth (Y) assuming a Y/Z ratio of ~2.4:1 (pre-wave erosion). The Picnic Point lozenge has a ~115 m length (X), a ~14 m width (Z) and an estimated 90 m depth (Y). These estimated Y dimensions are based on pebble shapes in Spry and Burns (1972, figures 3, 5 and 9). Both lozenges have synformal fold "keels", where the synforms have inclined plunging macro-geometry. Both synformal cores are enveloped and bounded by high strain zones of phyllite, quartz-mica schist and schistose quartzite (pink sheets). The pod/lozenges have X/Z ratios of ~10 : 1 (Seagull Islet lozenge) and ~8 : 1 (Picnic Point lozenge). The core of the Seagull Islet lozenge is shown by the black dashed oval outline containing the synformal hinge and the refolded central zone (Sewer Vent fold stack). The Picnic Point lozenge appears as a southern, boudinaged continuation of the quartzite that makes up the Seagull Islet lozenge.

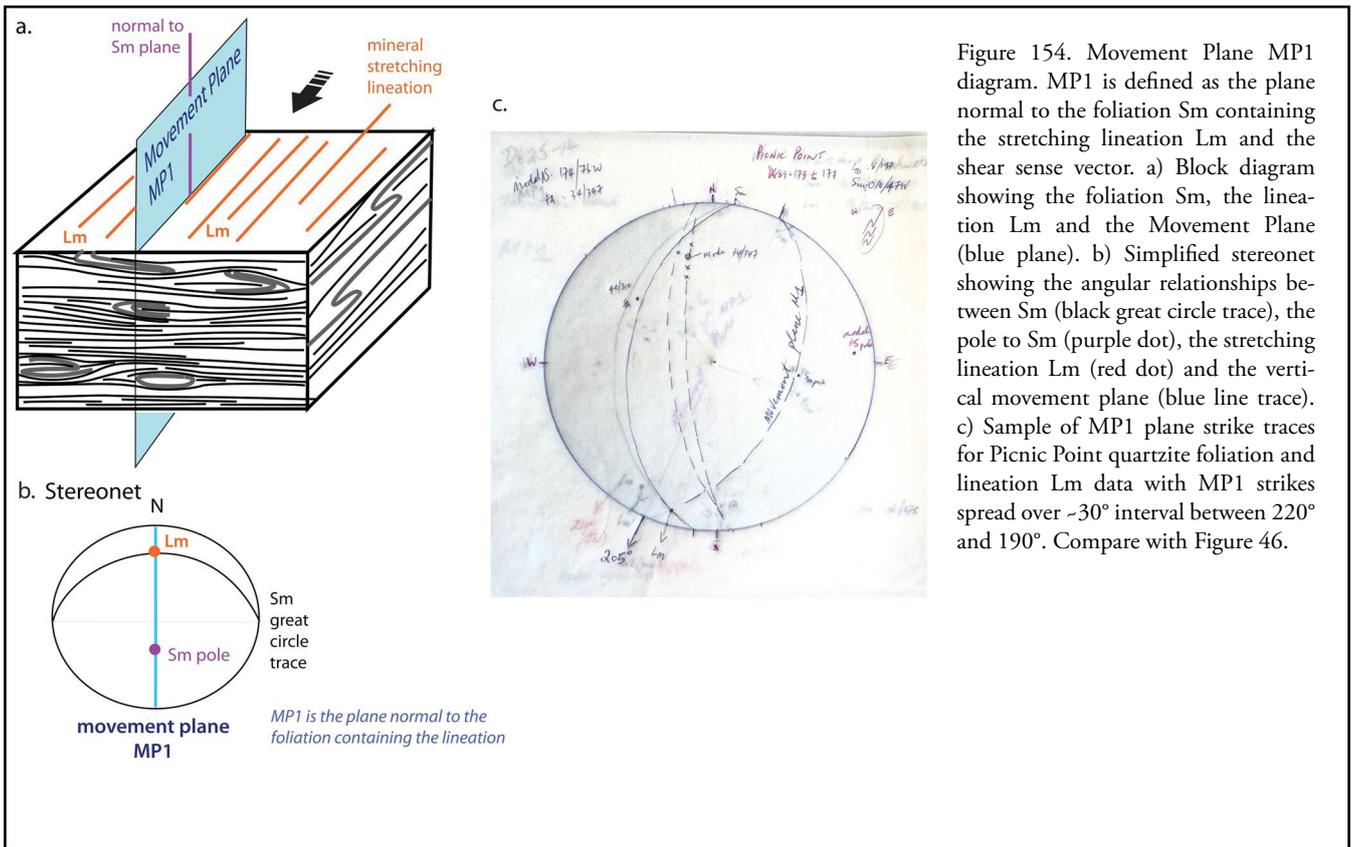


Figure 154. Movement Plane *MP1* diagram. *MP1* is defined as the plane normal to the foliation *Sm* containing the stretching lineation *Lm* and the shear sense vector. a) Block diagram showing the foliation *Sm*, the lineation *Lm* and the Movement Plane (blue plane). b) Simplified stereonet showing the angular relationships between *Sm* (black great circle trace), the pole to *Sm* (purple dot), the stretching lineation *Lm* (red dot) and the vertical movement plane (blue line trace). c) Sample of *MP1* plane strike traces for Picnic Point quartzite foliation and lineation *Lm* data with *MP1* strikes spread over ~30° interval between 220° and 190°. Compare with Figure 46.

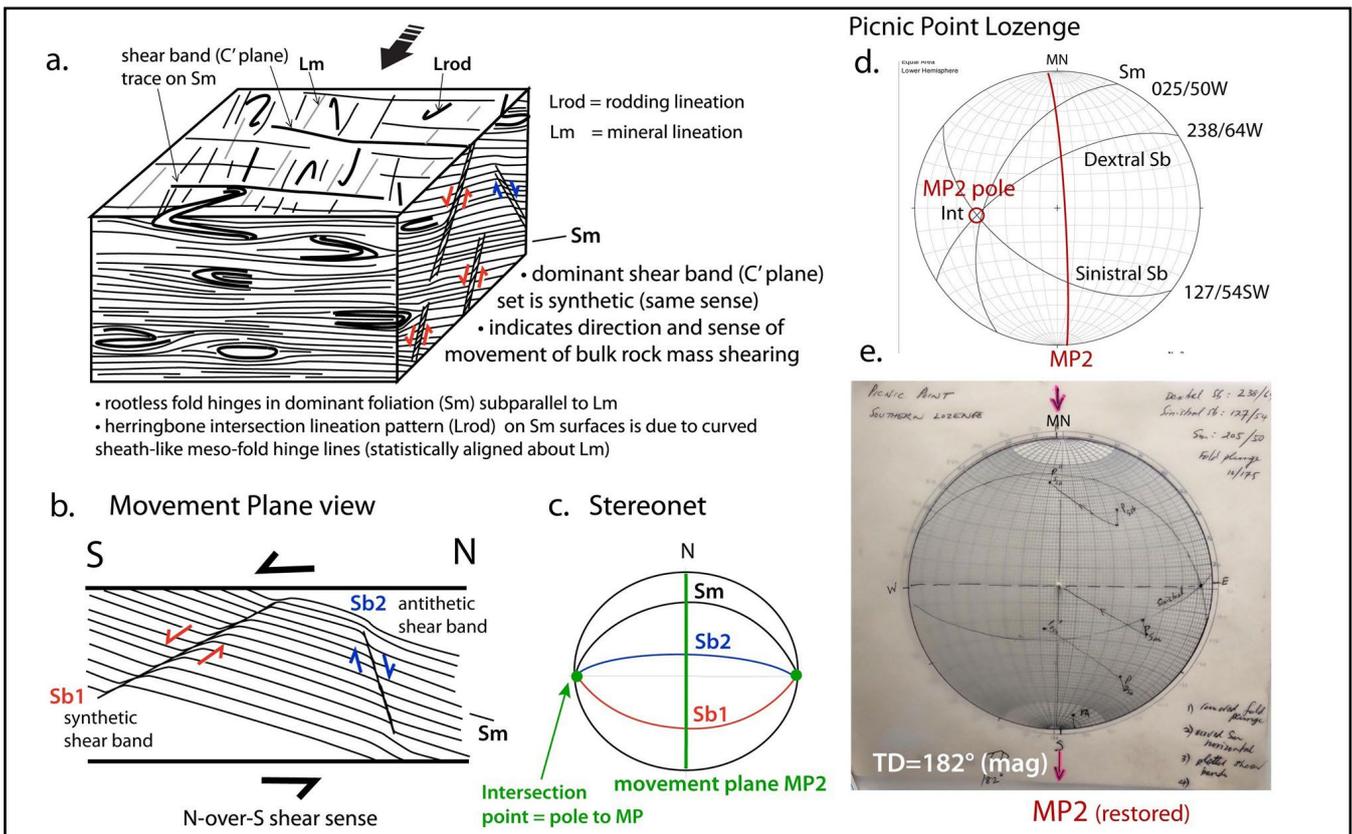


Figure 155. Movement Plane *MP2* diagram. *MP2* is defined as the plane normal to the foliation *Sm* and normal to the line of intersection traces of shear bands (*Sb*) on the foliation. It also contains the shear sense vector. a) Block diagram showing the foliation *Sm*, rodding lineations (*Lrod*), mineral lineation (*Lm*) and with the side of the block (the movement plane) showing both synthetic (red arrows) and antithetic (blue arrows) shear bands. b) Movement plane view (side of the block) showing the synthetic (red arrows) and antithetic (blue arrows) shear bands and the angular relationships to the foliation and the related shear sense (black arrows). c) Simplified stereonet showing the angular relationships between *Sm* (black great circle trace), the synthetic shear band (*Sb1*) red great circle trace, the antithetic shear band (*Sb2*) blue great circle trace, the intersection between the shear bands and the foliation (*Lint*) and the vertical movement plane (green line trace). Note the movement plane is normal to the foliation/shear band intersection (*Lint*). d) Stereonet of dextral and sinistral shear band (*Sb*) set within the Picnic Point Shear Lozenge (see Figure). e) Restored *MP2* movement plane with removal of the regional fold plunge and return of *Sm* to the horizontal. Note the Transport Direction vector (*TD*) is towards 182° (magnetic).

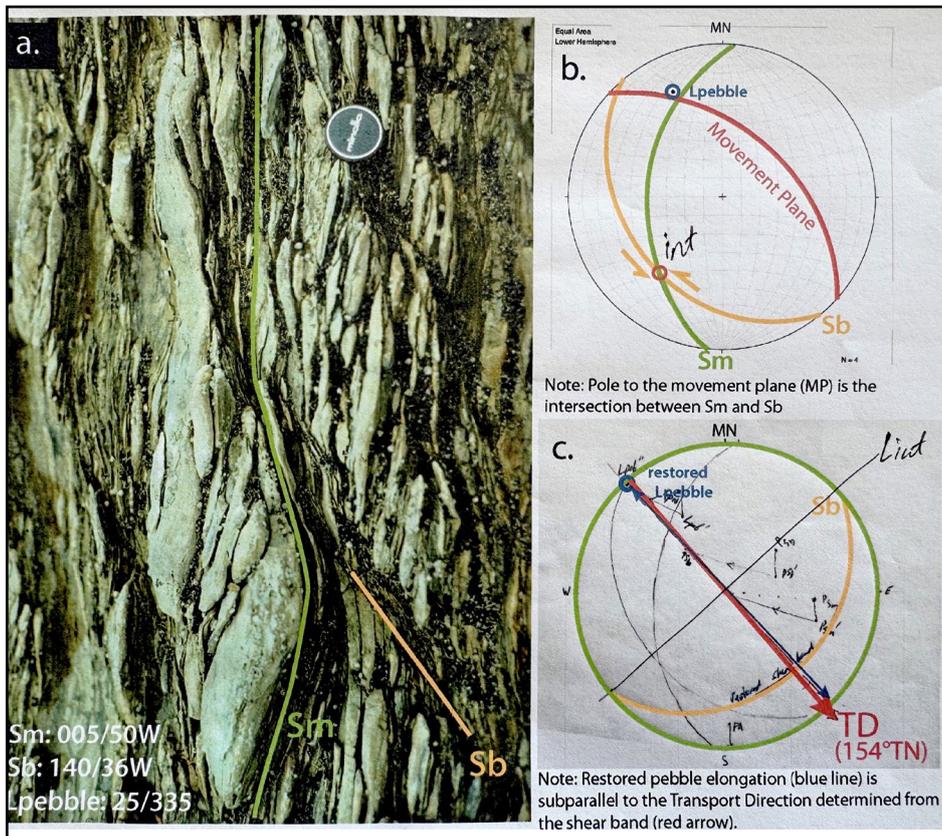


Figure 156. Example of sinistral shear band (Sb) in schistose pebbly quartzite of the Picnic Point wave cut platform. a) Photograph of shear band (Sb) in west-dipping foliation (Sm). b) Stereonet with the attitudes of the measured structural elements shown by the variously coloured great circles. c) Restored structural relationships to determine the shear band strike with the foliation restored to the horizontal after removal of the regional fold plunge (Forth Anticline). Note the transport direction (TD) is 154° (magnetic).

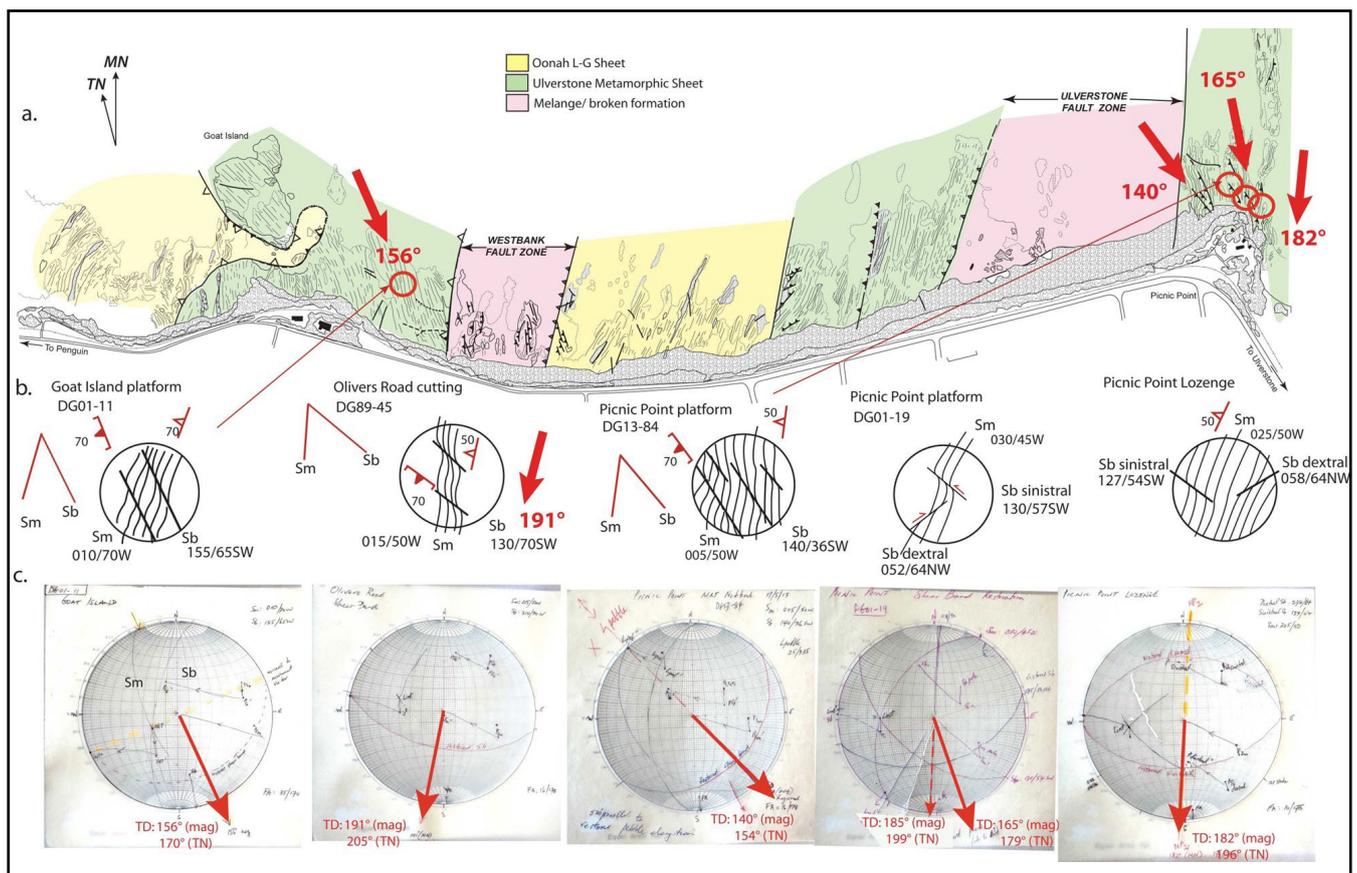


Figure 157. Total shear band transport direction (TD) data for the West Ulverstone coastal segment. a) Formline map with fault slices and summary transport vectors (red arrows). b) Outcrop sketch structural relationships with measured attitude data for structural elements (Sm) and shear bands (Sb). c) Stereonets showing shear band restoration after removal of the regional fold plunge and restoration of Sm to the horizontal.

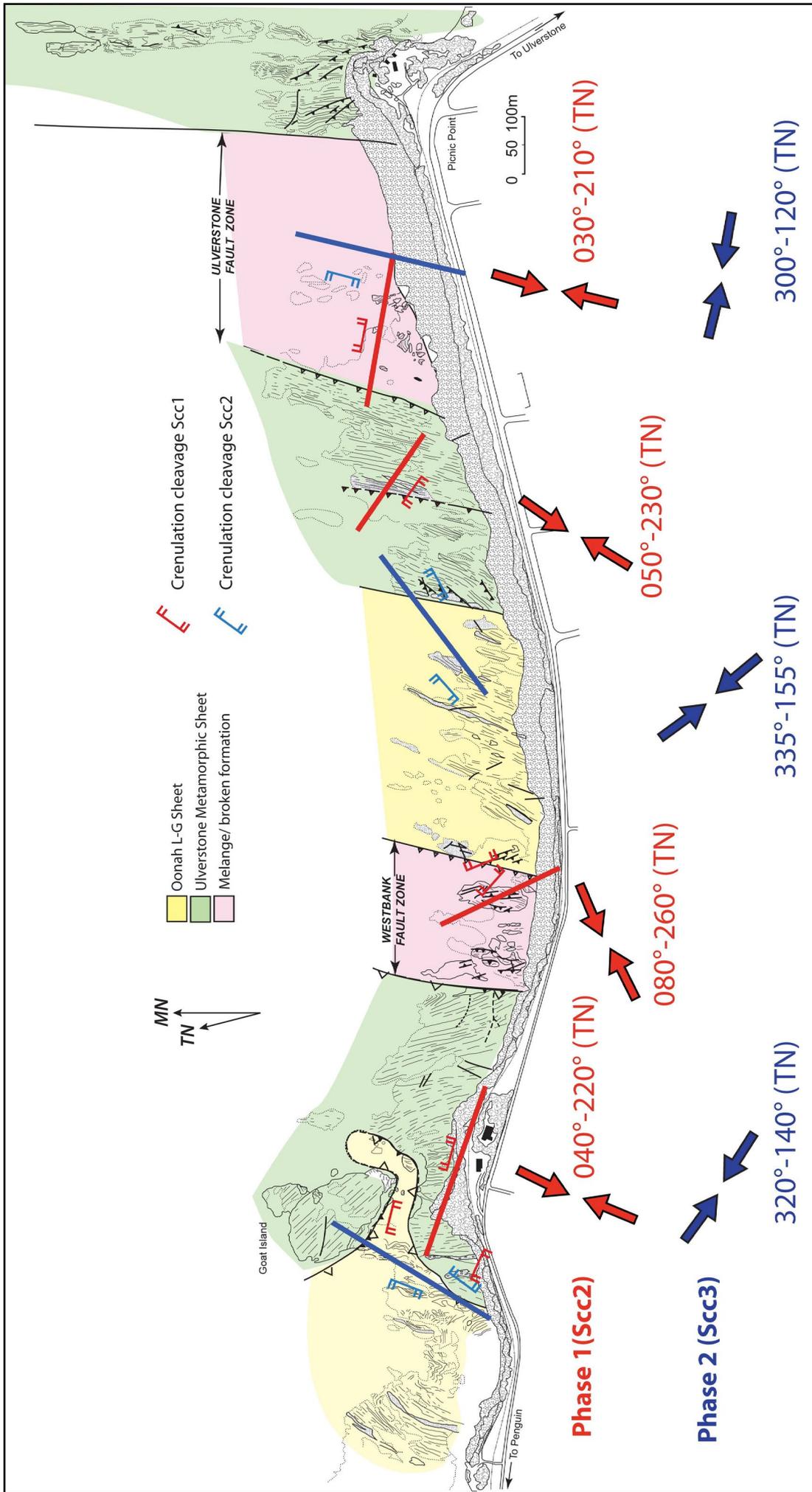


Figure 158. Summary map of crenulation cleavage patterns across the West Ulverstone Imbricate Zone. Crenulation cleavage orientations as coloured strike traces where Scc2 with NW-strike is shown by the pink traces, and Scc3 with NE-strike shown by the blue traces. The inferred shortening directions (assumed orthogonal to the Scc) are shown by the heavy red (Phase 1 Scc) and blue arrows (Phase 2 Scc). Phase 1 is interpreted as part of the Early Cambrian sheet emplacement exhumation stage. Phase 2 is interpreted as part of the younger Devonian reverse faulting event with east-directed transport.

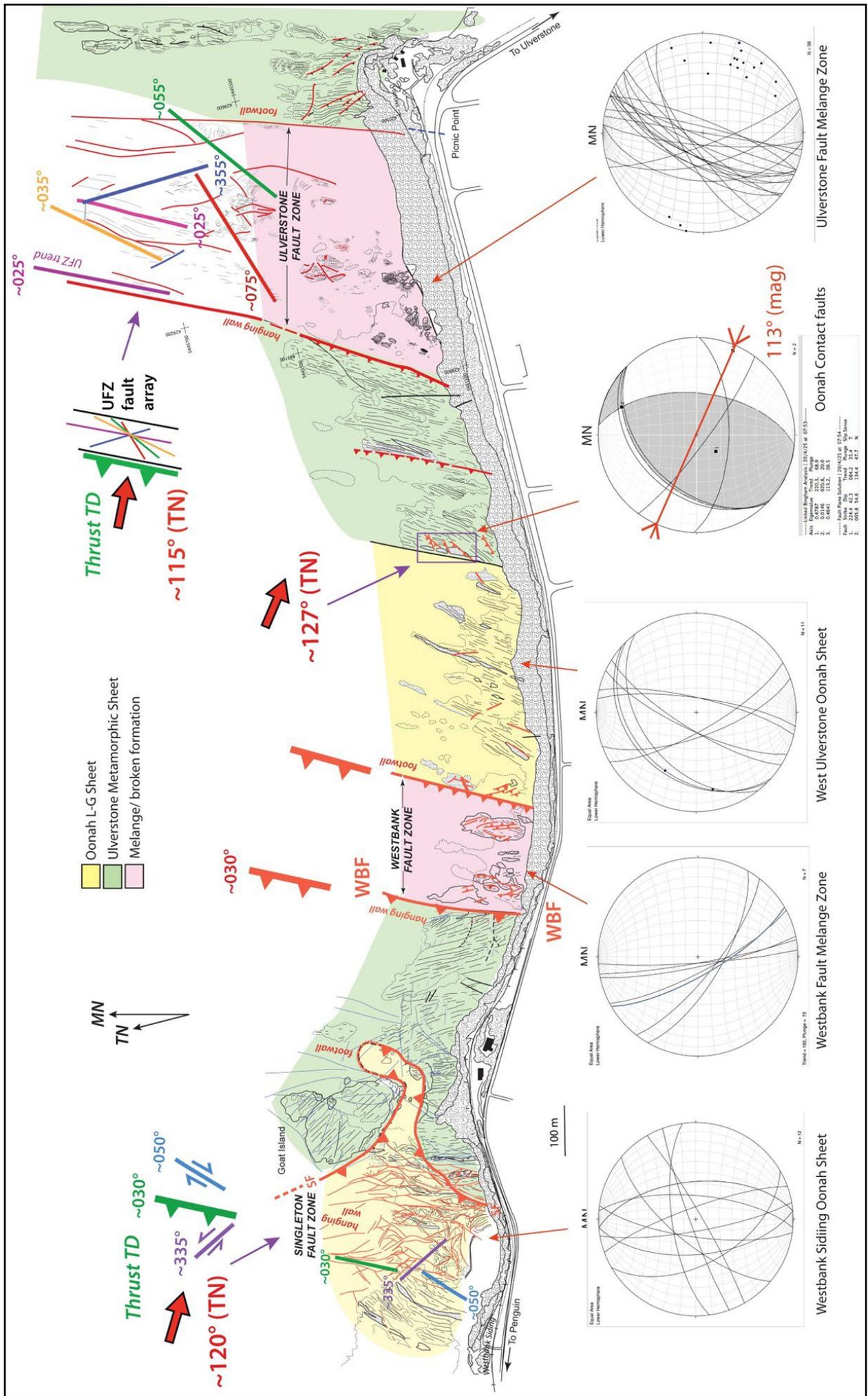


Figure 159. Fault pattern and transport vectors for the faults of the West Ulverstone Imbricate Zone. Summary fault trace trends are shown for the Singleton and Ulverstone Fault Zones (compare with Figures X and X). Stereonets along the base of the figure show the fault attitudes as great circle traces for the different lithotectonic elements. Fault compression vectors are shown by the heavy red arrows and show a general ESE-WNW compression with an overall ESE transport sense.

#### 5.4.4 Fault Patterns

Secondary fault patterns within the major Singleton and Ulverstone Fault Zones reflect the impact of the late stage Devonian, east-directed reverse faulting. This requires 1) reactivation and renewed faulting within the Early Cambrian subduction/exhumation mélangé interfaces and 2) splay development off the Middle Cambrian extensional faults that have offset the Oonah and Ulverstone Sheets.

1. The Ulverstone Fault Zone with an overall  $\sim 025^\circ$  trend consist of a series of linked to discontinuous faults within the  $\sim 400$  m wide fault zone mélangé. The faults internal to the mélangé zone have  $\sim 025^\circ$ ,  $\sim 035^\circ$ ,  $\sim 055^\circ$ ,  $\sim 075^\circ$  and  $\sim 355^\circ$  trends (Figures 139b and 159) The fault pattern suggests hanging wall up, reverse fault movement with an  $\sim 115^\circ$  transport direction (TD).
2. The Singleton Fault Zone is dominated a series of steeply dipping, reverse faults in the immediate hanging wall of a steep, west-dipping fault ramp with complex geometry in the vicinity of Goat island (Figure 159). The zone is defined by an array of  $\sim 335^\circ$ ,  $030^\circ$  and  $050^\circ$  trending faults that form a complex fault network (Figures 79 and 159). The pattern suggests hanging wall up, reverse fault movement with an  $\sim 120^\circ$  transport direction (TD).

The fault summary map (Figure 159) shows the overall southeast-directed transport within the West Ulverstone Imbricate Fault Zone. The major fault breaks and the faults internal to the major mélangé zones all reflect this younger, late stage Devonian fault activation and reactivation. The fault patterns vary between different parts of the major Oonah and Ulverstone slices, as well as within the Singleton, Westbank and Ulverstone fault zones (stereonet, Figure 159).

#### 5.4.5 Transport Direction Summary

Transport directions are summarised with vector means for the respective emplacement events and fault activation/reactivations (Figure 160). These are:

##### 1. Early Cambrian subduction/exhumation sheet emplacement

MP1 (Lm-Sm derived) has a vector mean  $\sim 204^\circ$  (n=3) (Figure 154)

MP2 (shear band derived) has a vector mean  $\sim 170^\circ$  (n=5) (Figure 157)

Sc2 (phase 1 shortening) vector mean  $\sim 230^\circ$  (n=4) (Figure 158)

##### 2. Late stage Devonian Fault activation/reactivation:

Fault network pattern:  $\sim 115^\circ$  and  $\sim 120^\circ$  (Figure 159)

Sc3 (phase 2 shortening) vector mean  $\sim 138^\circ$  (n=3) (Figure 158)

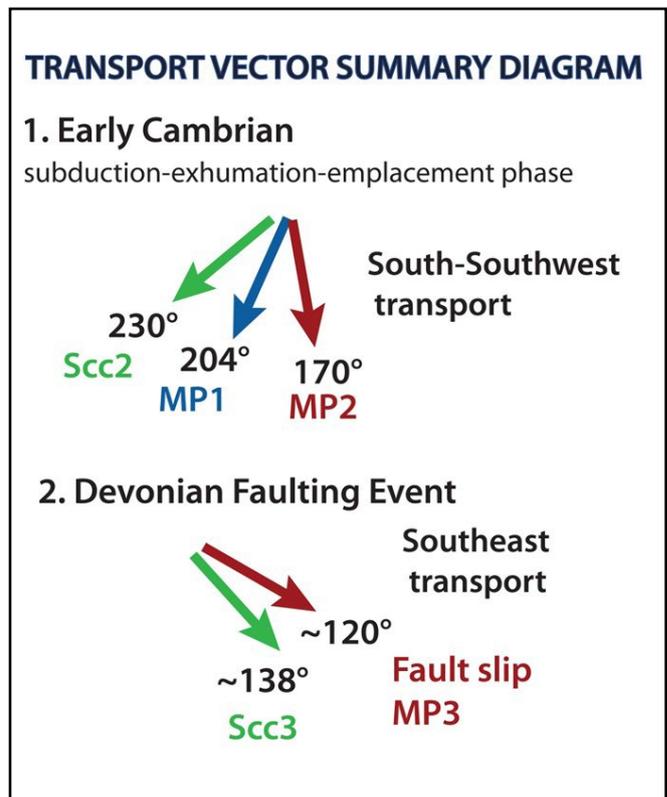


Figure 160. Transport Vector summary diagram for the Ulverstone Sheet and Ulverstone-Oonah Sheet slices. 1) the Early Cambrian subduction-exhumation-emplacement phase, and 2) the Devonian thrust reactivation phase.

#### 5.5 Devonian Reactivation of the Internal-External Zone Interface

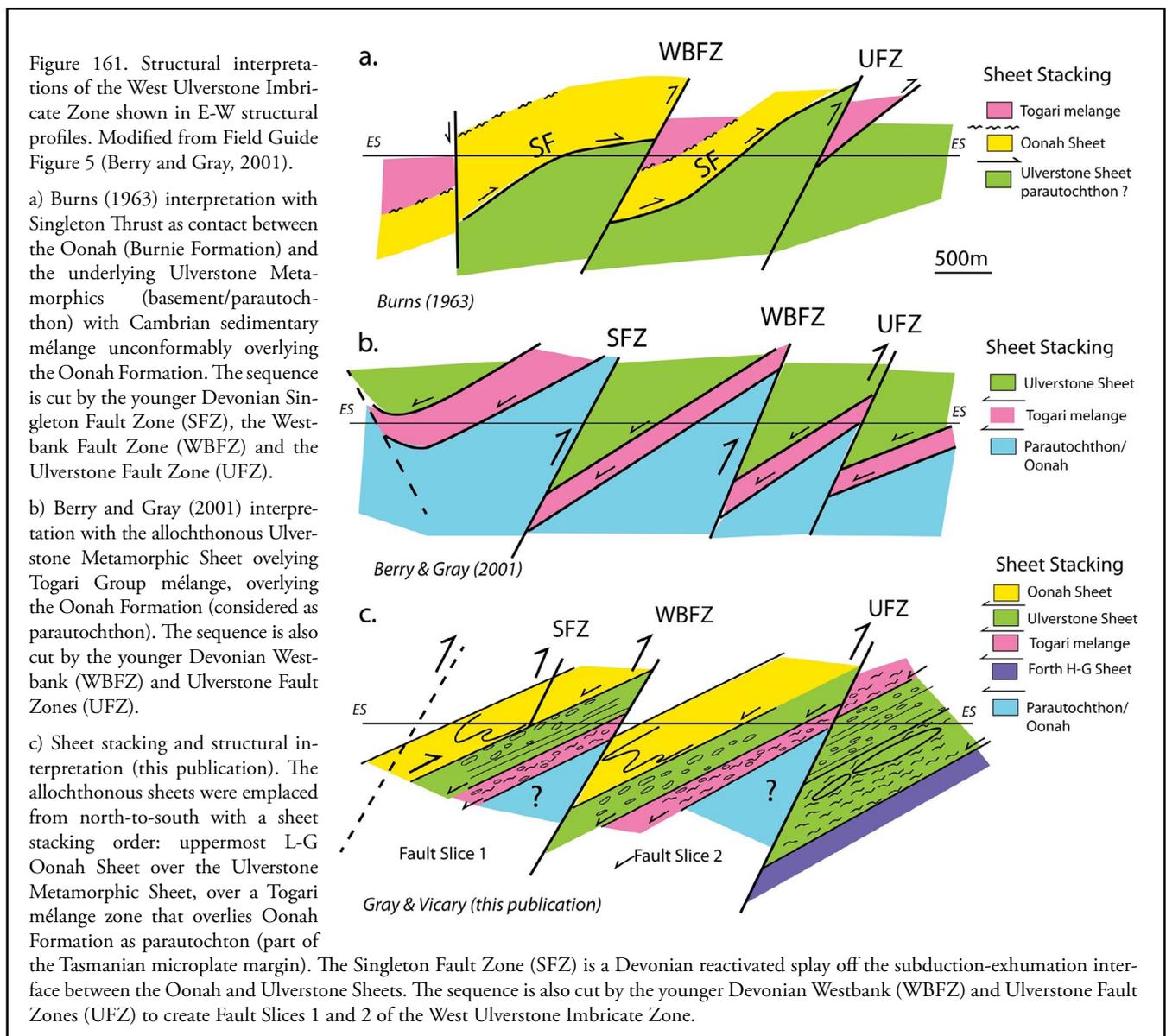
Two historical and radically different structural interpretations have previously been made of the stacking order and the nature/displacement sense of faulting in this coastal sequence. The interpretations include (Figure 161):

1. Pre-plate tectonic Interpretation (Burns, 1963a): The litho-stratigraphy has "Cambrian" sedimentary mélangé (now considered Togari Group equivalents) overlying L-G Oonah Formation thrust over the Ulverstone Metamorphics (basement) along the Singleton Thrust (SF). The package is cut by two east-directed, steeper reverse faults, the Westbank Fault (WBFZ) and the Ulverstone Fault (UFZ).
2. Allochthonous Model (Berry and Gray, 2001): The model reconstruction has an overall stacking of Ulverstone Metamorphics overlying Togari Group correlates overlying Burnie Formation. The allochthonous Ulverstone Metamorphic Sheet has been emplaced over Oonah Formation (considered as parautochthon) along zones of Togari mélangé generated in early Cambrian south-directed, obduction thrusting. These include the Westbank and Singleton Fault Zones that are reactivated and cut by younger, steep west-dipping Devonian faults (Singleton Thrust and two unnamed thrusts).

3. West Ulverstone Imbricate Zone Fault Reconstruction (this publication): The reconstruction involves Early Cambrian, south-directed obduction thrusts (the Singleton, Westbank and Ulverstone Faults) with a stacking order from top to bottom of Oonah Sheet overlying the Ulverstone Metamorphic Sheet along Togari mélangé. This package overlies parautochthon (Oonah Formation) in the fault slices of the West Ulverstone Imbricate Zone, whereas at deeper levels the Ulverstone Sheet structurally overlies the H-G Forth Metamorphic Sheet. This stack/sequence (Figure 162a) was segmented by Middle Cambrian extensional faults (Figure 162b) that were reactivated by Devonian east-directed reverse faulting by development of younger, short-cut, reverse/thrust fault splays (Figure

162c). The model also requires overstepping of the exhumed and obducted sheets onto the Tasmanian microplate margin (see Figure 162).

The presence of Cambrian volcano-sedimentary rocks in a ~5 km wide, graben-like zone just south of the West Ulverstone coastal exposures (Cdsv and Cdsk, Figures 72 and 73) suggests that Middle Cambrian extensional faulting extends to the coast as steeply dipping faults (fault sets 3 and 5, Figure 3 and green and blue faults, Figure 72). The faults include the Lodders Point Fault and the Devonian reactivated Westbank and Ulverstone Faults. Normal-fault offset and displacement of the subduction-exhumation and obduction stack (Figure 162a) must also influence the profile reconstruction (Figure 162).



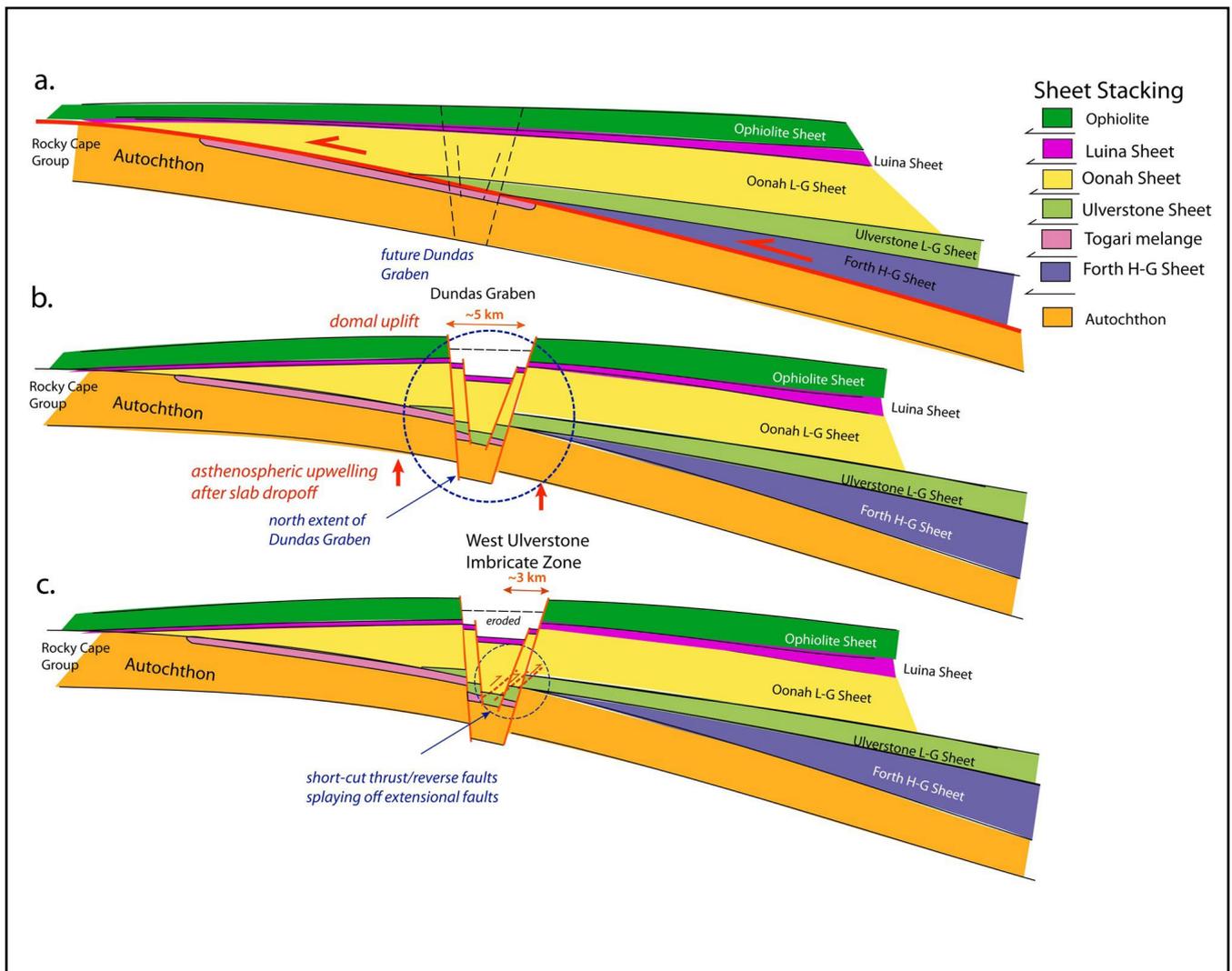


Figure 162. Idealised, schematic structural profile reconstruction of the West Ulverstone Imbricate Zone utilising the Middle Cambrian extensional faults defining the northern extent of the Dundas Graben.

- a) a simple initial Early Cambrian stacking model due to subduction-exhumation of the Oonah, Ulverstone and Forth Sheets followed by obduction of the seafloor substrate (Luina Sheet) and the oceanic lithosphere (ophiolite).
- b) Dundas Graben development with trough.

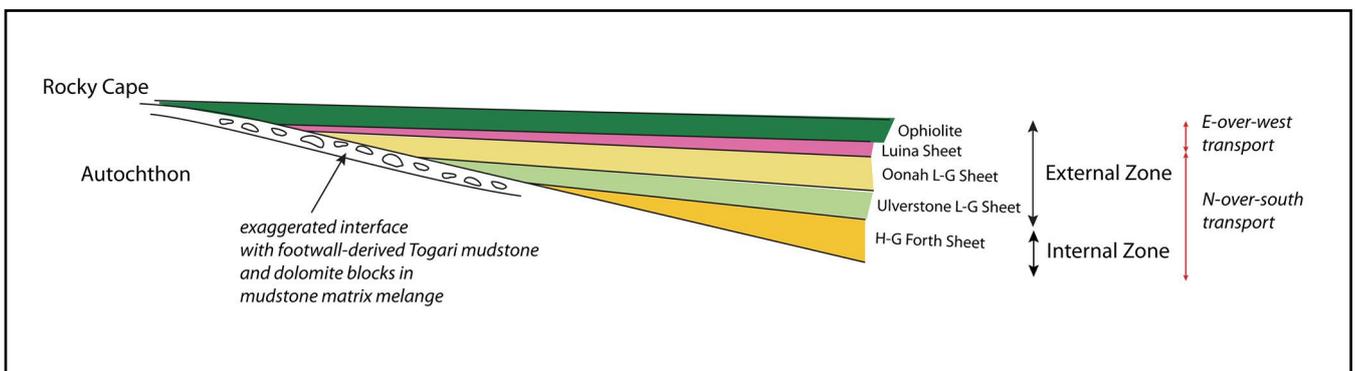


Figure 163. Overstepping model for incorporation of Togari blocks into the basal shear zones of the Luina, Oonah and Ulverstone Sheets.

## 6.0 TECTONIC IMPLICATIONS OF THE FORTH AND ULVERSTONE METAMORPHIC SHEETS AND NORTH COAST GEOLOGY

Important structural observations from Northern Tasmanian geology provide important constraints on the tectonic evolution of Tasmania. These include:

- South transport of Mesoproterozoic and Neoproterozoic sequences.
- Subducted to different levels and exhumed with north-over-south shear sense.
- The North coast geology involves a simple stacking of Luina/Oonah/Ulverstone/ Forth Sheets. The basal contact of the Oonah Sheet has been modified by younger, Devonian faulting as part of the West Ulverstone Imbricate Zone. The presence of Togari correlate blocks of dolostone, red, black and greenstone mudstone indicate a breccia mélange along the basal contact of the Oonah and Ulverstone Sheets, suggesting foot wall derived blocks of Togari Group from the underlying autochthon/parautochthon. This requires overstepping of sheets at their leading edges to:
  - ◇ give a structural/tectonic onlap; and
  - ◇ pluck off Togari blocks in their footwall (Figure 163).
- Togari Group is the youngest stratigraphic part of the subducted margin, such that the Togari mélange occurs at the highest structural level. It is incorporated into the base of the ophiolite, at the base of the Luina Sheet and the base of the Oonah Sheet.
- The Ulverstone-Forth coastal section has had a complex faulting history with offsets and displacements that are necessary to explain the observed juxtaposition of sheets and the incorporation of Togari blocks in sheet-contact zone mélanges. These are:
  - ◇ N-over-S emplacement of the Early Cambrian exhumation/obduction stack where fault bounded sheets show hanging wall-up emplacement with overstepping of sheets upwards through the stack.
  - ◇ W-down Middle Cambrian normal faulting to create the north part of the Dundas Graben.
  - ◇ W-over-E Devonian thrusting with short-cut thrusts initiating off the steep west-dipping normal faults.
- The North coast shows a different sheet stacking and transport sense to the Tyennan Domain with discordance across the Fossey Graben suggesting a major change in structural/tectonic evolution across the graben.

- The structural discordance across the Fossey Graben supports an inferred east-west trending transform fault in the Cambrian subduction margin (see Gray and Vicary, 2025, fig. 139). This was a fundamental break in the east-directed subduction of the Tasmanian microcontinent. The inferred transform fault most likely facilitated the middle Cambrian development of the E-W trending Fossey Graben and resulted in a change in plate motion to the north of the transform.

## 7.0 CONCLUSIONS

Northern Tasmanian coastal exposures show the nature of the sheet interfaces and structural relationships both within and between the L-G sheets (Oonah and Ulverstone Sheets) of the External Zone and the high-grade sheets (Forth Metamorphic Sheet) of the Internal Zone of the proposed Cambrian subduction-exhumation-obduction system of Berry (2014).

A change in the order of sheet stacking and transport direction between northern Tasmania coastal exposures and the central Tasmanian Tyennan Domain, the Internal Zone proper, requires the presence of a transform break in the Cambrian east-dipping, subduction system and a change in plate motion to the north of the inferred transform.

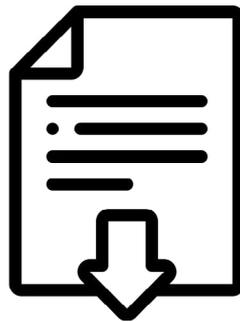
## 8.0 ACKNOWLEDGEMENTS

- Kerry Burns for first introducing me to the complex structural geology of Picnic Point/Seagull Islet in February, 1972 as part of a Macquarie University PhD project.
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- Chris Large for editing and formatting this Tasmanian Geological Survey publication.

## 9.0 REFERENCES

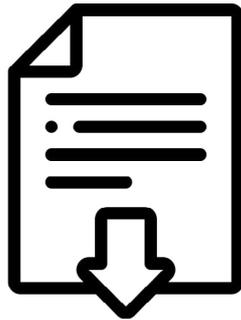
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# APPENDIX A



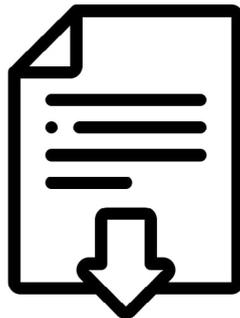
Ulverstone foreshore georeferenced satellite images

# APPENDIX B



**Picnic Point Kink Band Study**

# APPENDIX C



Goat Island Photography



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Government

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